

LETTER • OPEN ACCESS

## How food secure are the green, rocky and middle roads: food security effects in different world development paths

Recent citations

- [Modelling alternative futures of global food security: Insights from FOODSECURE](#)  
Hans van Meijl *et al*

To cite this article: Hans van Meijl *et al* 2020 *Environ. Res. Commun.* **2** 031002

View the [article online](#) for updates and enhancements.

## Environmental Research Communications



## LETTER

## How food secure are the green, rocky and middle roads: food security effects in different world development paths

## OPEN ACCESS

## RECEIVED

4 September 2019

## REVISED

13 February 2020

## ACCEPTED FOR PUBLICATION

27 February 2020

## PUBLISHED

19 March 2020

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Hans van Meijl<sup>1,3</sup> , Andrzej Tabeau<sup>1</sup>, Elke Stehfest<sup>2</sup>, Jonathan Doelman<sup>2</sup> and Paul Lucas<sup>2</sup> <sup>1</sup> Wageningen Economic Research, Wageningen University and Research, The Hague, The Netherlands<sup>2</sup> PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands<sup>3</sup> Agricultural Economics and Rural Policy Group, Wageningen University, Wageningen, The NetherlandsE-mail: [Hans.vanmeijl@wur.nl](mailto:Hans.vanmeijl@wur.nl) and [okhansvanmeijl@wur.nl](mailto:okhansvanmeijl@wur.nl)**Keywords:** food security, food access, shared socio-economic pathway, scenario, CGE modelSupplementary material for this article is available [online](#)**Abstract**

The Sustainable Development Goals (SDGs) address food and nutrition security with goal number two. Food and nutrition security is a complicated issue, and understanding its future requires insights into (i) food availability, (ii) food access, (iii) food utilisation, and (iv) food stability. Not all these dimensions are covered by the SDG2 and its indicators. A unique feature of this paper is that it focuses on the first three dimensions of food security in addition to the prevalence of undernourishment (SDG indicator 2.1.1). Here we explore future food security in the absence of dedicated policies, to derive the ‘policy gap’ for this goal. The internationally agreed shared socio-economic pathways (SSPs) are quantified using a computable general equilibrium model (MAGNET) coupled with an integrated assessment model (IMAGE) that enable a linkage between income and expenditures given segmented labour markets. Based on the three dimensions of food security our results showed a less optimistic outlook than based on previous studies. Food availability is projected to improve in all 5 SSP scenarios, except South Asia in SSP3 due to serious land constraints. As a result, the number of undernourished people decreases in most scenarios, becoming increasingly concentrated in Sub-Saharan Africa and South Asia. However, undernourishment stays high in SSP4 (550 million people) and increases to over two billion people in SSP3. Food access generally improves due to higher agricultural and non-agricultural wages of unskilled workers. However, due to lock-in effects the wages of unskilled agricultural workers might decline, leading to reduced food access in SSP3, SSP4 and SSP2. The indicator of food utilisation shows food security problems for Sub-Saharan Africa in SSP3 and SSP4. Our results indicate that food security problems remain and that effective policies are needed to achieve food security for all.

**1. Introduction**

The Sustainable Development Goals (SDGs) and possible impacts of climate change and climate change mitigation (Hasegawa *et al* 2015, 2018, van Meijl *et al* 2018) put long-run food and nutrition security high on the political and scientific agenda. The SDGs address food and nutrition security in SDG2, i.e. to ‘End hunger, achieve food security and improved nutrition and promote sustainable agriculture’ (UN 2015). Model-based projections of future food security can provide insights into the ‘policy gap’ to that goal. However, large-scale studies on future global food security and malnutrition, are scarce, mostly due to the complex and small-scale determinants of food security (van Dijk and Meierink 2014). The interest in potential impacts of climate change and climate mitigation on food security has created the need for model-based analysis of future food security. These studies on the likely impacts of climate change or mitigation generally focus mostly on future food supplies, sometimes translated to the number people at risk of hunger (Hasegawa *et al* 2015, 2018,

van Meijl *et al* 2018, 2020). However, food and nutrition security is a much more complicated issue, and understanding its future requires insights into income distribution, purchasing power, political processes, and institutional change (Barrett 2010, Godfray *et al* 2010). Furthermore, developments in food and nutrition security are highly region-specific and not one to one related with income per capita growth. For example, in the period 1990–2015 the number of malnourished people decreased from 1 billion to 800 million people on a global level. However, in the same period the number of malnourished people increased from 175 to 220 million in Sub-Saharan Africa (FAO 2015), despite a 30% growth in per capita income (Worldbank 2017). Uneven distribution of income growth in favour of richer people is one of the driving forces behind this result.

A widely accepted definition of food security is ‘Food security exists when 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 1998). This is reflected in SDG target 2.1 (‘By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round’). The FAO definition consists of four key dimensions: availability (i.e. sufficient quantities of food; ‘sufficient’), access (i.e. adequate resources to obtain food; ‘access’), utilisation (i.e. ‘nutritious and safe’ diets, and clean water) and stability (i.e. the temporal dimension of the other three dimensions; ‘at all times’). The translation of the FAO definition to the four dimensions and their labelling as availability, access, utilisation and stability is further detailed in (FAO 2008a, 2012). Since 2011 changes in global food security have been monitored using the FAO suite of food security indicators (Committee on World Food Security 2011, table 2). We use here these dimensions of food security as suggested by FAO, which have a broader scope than the indicators defined for SDG2, and are therefore better suited to identify future risks to food security, while for monitoring progress the prevalence of undernourishment (SDG indicator 2.1.1) might suffice.

The four dimensions of food security have not been well captured in major scenario studies (van Dijk & Meijerink 2014). Scenario studies with a focus on food security often use a set of three indicators: food prices (in most cases for cereals), food availability (food production or kilocalories per person per day) and hunger indicators (prevalence of undernourishment or child malnutrition) (Nelson *et al* 2013, Hasegawa *et al* 2015, 2018, van Meijl *et al* 2018, 2020). Food prices are seen as indicative for food access (see below). For **food availability**, some studies use food availability directly as indicator, while others derive further indicators of undernourishment. These undernourishment (or hunger) indicators are typically based on rules to translate average per capita consumption together with a food distribution indicator to the population below a certain level of food intake or a specific physiological state (i.e. child underweight).

**Food access** is more complicated to measure than food availability as it indicates the ability of people to buy sufficient food, i.e. food purchasing power, including people’s income and the price developments of their specific diet. The impact of food prices on food purchasing power differs between various types of households, for example between rural and urban populations, as well as between producers and consumers of food. High food prices in general negatively impact food access of consumers, especially in urban areas, while for farmers they raise their income and therefore might positively impact their food access (Swinnen 2011). The opposite is true for low food prices. **Food utilisation** is about ‘safe and nutritious food which meets their dietary needs’ (FAO 1998). It relates to nutritional status and is commonly understood as the way the body makes the most of various nutrients in the food, depending, among others, on sufficient energy and nutrients, food preparation and diversity of the diet (Pangaribowo *et al* 2013, Rutten *et al* 2016). Finally, **food stability** requires adequate access to food on a periodic basis. Adverse weather conditions, political instability and economic factors (unemployment, rising food prices) may impact the stability and thereby the food security status of people (FAO 2008a). Therefore, although food security is primarily addressed by SDG2 it depends on many other developments, targeted under different SDGs, including (but not exclusively) no poverty (SDG1), clean water and sanitation (SDG6), decent work and economic growth (SDG8), climate action (SDG13) and peace, justice and strong institutions (SDG16).

A new scenario framework has been developed to allow exploring possible future challenges with respect to climate change (van Vuuren *et al* 2014). The so-called shared socio-economic pathways (SSPs) are five distinct global pathways describing the future evolution of key aspects of society that would together imply a range of challenges for mitigating and adapting to climate change (O’Neill *et al* 2012). While these scenarios were created to support the climate change research community, their definition is broad enough to serve the much broader global change research community (van Vuuren *et al* 2014, O’Neill *et al* 2017). In addition to food security, also the SSP scenario literature mostly addresses food availability (Nelson *et al* 2013, van Meijl *et al* 2018) and derived indicators such as hunger (Hasegawa *et al* 2015, 2018, van Meijl *et al* 2020). We use the SSP scenario framework to explore the consequences of different world development paths on future food and nutrition security. We use an economic computable general equilibrium (CGE) model (MAGNET) and an integrated assessment model (IMAGE), which have provided the marker scenario for SSP1 (Riahi *et al* 2017, van Vuuren *et al* 2017). CGE models connect labour markets, land markets and consumer markets and are able to play their role in the food security debate as they link income developments to consumption or expenditures (Smeets-Kristkova *et al* 2017, Doelman *et al* 2019, Mukhopadhyay *et al* 2018, Kuiper *et al* 2019). Next to food availability and the prevalence of

**Table 1.** Shared socio-economic pathway (SSP) scenario description, for more details, see Riahi *et al* (2017).

SSP	SSP name	Description
SSP1	Sustainability	A world that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Elements that contribute to this are an open globalised economy, rapid development of low-income countries, a reduction of inequality (globally and within economies), rapid technology development, low population growth and a high level of awareness regarding environmental degradation. More environmental awareness reduces food waste, the appetite for meat as well as making land use regulation stricter.
SSP2	Middle of the Road	A business as usual scenario. In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historical rates, and slowly decreasing fossil fuel dependency.
SSP3	Regional Rivalry	A world which is separated into regions characterised by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them. Countries focus on achieving energy and food security goals within their own region. The world has deglobalised, and international trade, including energy resource and agricultural markets, is severely restricted. Population growth in this scenario is high as a result of limited improvements in education and low economic growth.
SSP4	Inequality	A highly unequal world both within and across countries. A relatively small, rich global elite is responsible for much of the emissions, while a larger, poorer group contributes little to emissions and is vulnerable to impacts of climate change, in industrialised as well as in developing countries. Governance and globalisation are effective for and controlled by the elite, but are ineffective for most of the population. Land use regulation is strict in high/middle income countries whereas it is unsuccessful in low income regions.
SSP5	Fossil-fuelled development	This world stresses conventional development oriented toward economic growth as the solution to social and economic problems through the pursuit of enlightened self-interest. The preference for rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation. Efficiency is high in agriculture but also demand is high with a high preference for meat. Lower socio-environmental challenges to adaptation result from attainment of human development goals, robust economic growth, highly engineered infrastructure with redundancy to minimise disruptions from extreme events, and highly managed ecosystems.

undernourishment we contribute specifically to better cover the food access dimension. This dimension can be proxied by the food purchasing power of certain labour types, as CGE models can deal both with the income of specific labour skill types and their expenditures for a food basket. In MAGNET segmented labour markets are introduced that prevent that all unskilled labour types earn the same wage and it enables that land and labour stay in certain sectors even if their remuneration is less (van Meijl *et al* 2006). Furthermore, we provide a proxy for food utilisation. Food stability is, given its short-run features, not taken into account in this medium- to long-term CGE model. Finally, we perform a sensitivity analysis concerning climate change impacts on food security to assess the robustness of our conclusions to climate change. In doing so we go beyond existing studies, by presenting a rich picture of this multi-dimensional problem and show how food security indicators differ between various population groups.

## 2. Methods

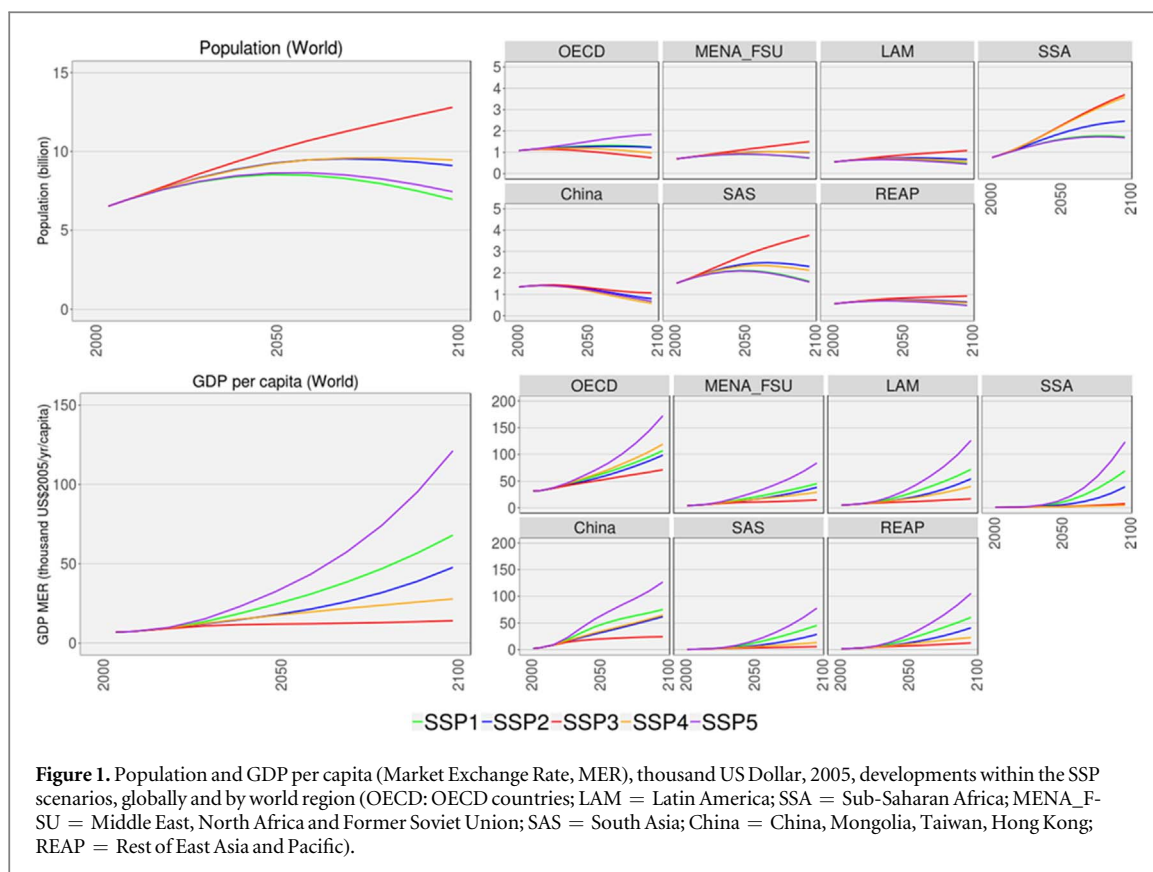
### 2.1. The SSP scenarios—setup and assumptions

A set of five socio-economic development pathways (SSP1—SSP5) until 2100 has been developed, serving as a consistent scenario framework. Each SSP is described by a quantification of future developments in population (KC and Lutz, 2017), urbanisation and economic development (Dellink *et al* 2017), and by a descriptive storyline to guide model parametrisation (O'Neill *et al* 2017). General characteristics of the SSP storylines, with a focus on food insecurity issues, are summarised in table 1.

Table 2 provides an overview of selected model-specific assumptions concerning agriculture, land use regulation, meat preferences, food waste and trade consistent with the SSP storylines (O'Neill *et al* 2017) and quantified by the authors. The interplay of these drivers and their effect on food demand in the MAGNET model simulations is further explained in the model description (section 2.2). Figure 1 shows the GDP per capita and population developments, respectively. The storylines have lower population growth in SSP1 and SSP5, middle level of growth in SSP2 and SSP4 and a high level of population growth in SSP3. Economic growth is highest in

**Table 2.** Scenario-specific characteristics for macro-economic development and specific land-use components (for more details, see Doelman *et al* 2018).

Scenario	SSP1	SSP2	SSP3	SSP4	SSP5
GDP growth	High in LICs, MICs; medium in HICs	Medium, uneven	Slow	Low in LICs, medium in other countries	High
Population growth	Low	Medium	High	Medium	Low
Inequality	Reduced across and within countries	Uneven moderate reductions across countries	High, especially within countries	High, especially across countries	Strongly reduced, across countries
Land-use change regulation	High	Medium	Low	From strong in HIC to low in LIC	Medium
Agricultural productivity	High	Medium	Low	High in HICs, and low in LICs	High
Trends in meat preferences	Negative preference shift for meat	Endogenous meat consumption dynamics	Positive preference shift for meat	Endogenous meat consumption dynamics	Positive preference shift for meat
Food waste	Reduced food waste ( one third lower than SSP2)	Current level of food waste (33% of production)	Higher level of food waste (one third higher than SSP2,)	Current level of food waste, as SSP2	Higher level of food waste, as SSP3
Trade in agricultural commodities	Abolishment of import tariffs and export subsidies.	Current import tariffs and export subsidies.	10% import tax for all agricultural products by 2050, for self- sufficiency concerns.	Abolishment of import tariffs and export subsidies and increase export cost of food form LIC to HIC.	Abolishment of import tariffs and export subsidies.



SSP1 and lowest in SSP3. GDP developments are in general opposite to population developments. The implications of these exogenous macro drivers for endogenous food demand are therefore uncertain as higher population means more mouths to feed, while lower total GDP means less total resources to spend on food. Furthermore, the scenarios are characterised by specific assumptions on meat preferences and food waste (table 2), consistent with the storylines (table 1). For example, in the environmentally friendly SSP1 food waste is reduced with one third and there is less preference for meat products, to reflect the lower environmental impact of consumption in this scenario. SSP1 is therefore also in line with the SDG, target 12.3 to halve food loss and waste by 2030. In SSP2 and SSP4 there are no additional exogenous shifts in waste and meat preferences. In SSP3 and SSP5 there are exogenous positive shifts in preferences for meat and food waste leading to higher environmental impact consumption and higher food demand. The latter is in line with findings of Hiç *et al* (2016).

## 2.2. Model used

The SSP scenarios are quantified using the agro-economic model MAGNET (Woltjer *et al* 2014) coupled to the IMAGE integrated assessment model (Stehfest *et al* 2014), and these scenarios are also described in detail in van van Vuuren *et al* (2017) and Doelman *et al* (2018). The MAGNET model is a multi-regional, multi-sectoral, applied general equilibrium model based on neo-classical microeconomic theory (van Meijl *et al* 2006, Nowicki *et al* 2009, Woltjer *et al* 2014). The core of the MAGNET database is the GTAP dataset (<https://gtap.agecon.purdue.edu/>, R8.1\_2007\_Feb2013). MAGNET assumes perfect competition, and producers are assumed to choose the cheapest combination of imperfectly substitutable labour, capital, land, natural resources and intermediates. The core of MAGNET is an input–output model, which links industries in value added chains from primary goods, over continuously higher stages of intermediate processing, to the final assembly of goods and services for consumption. MAGNET has a focus on modelling agriculture and food markets and assumes that products traded internationally are differentiated by country of origin (Armington 1969). Crucial for this study is the modelling of the land and other production factor markets, and the modelling of food demand. MAGNET includes a land supply function (van Meijl *et al* 2006, Dixon *et al* 2016) which specifies the relation between total agricultural land supply and the real land price given constraints related to biophysical availability (potential area of suitable land) and institutional factors (agricultural and urban policy, conservation of nature). Labour markets and the developments of wages per skill type are crucial for food access and in MAGNET there are two types of labour, skilled (professional) and unskilled (production) labour on the basis of occupational classifications (for more detail, see appendix). In MAGNET, factor markets are divided (segmented) into agricultural and non-agricultural labour and capital (van Meijl *et al* 2006). This reflects empirical evidence on imperfect mobility of labour (De Janvry *et al* 1991), and is thus an improvement

over other CGEs that assume perfect mobility. Food demand in MAGNET is endogenously determined by income changes, relative prices, and the dynamic income elasticities of food demand. These price feedbacks are absent in exogenous food demand models (e.g. Bodirsky *et al* 2015, Pradhan *et al* 2016, Bijl *et al* 2017), and arise from price changes due to increase total demand (resulting from population growth or bioenergy use), and changes in the supply side. Food waste and preference changes are exogenous scenario-specific assumptions. A lower food waste reduces the demand for food.

IMAGE is an integrated assessment model framework that simulates global and regional environmental consequences of changes in human activities (Stehfest *et al* 2014). The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters on the basis of a geographical grid of 30' by 30' or 5 by 5 min (depending on the variable). The model has been designed to analyse large-scale and long-term interactions between human development and the natural environment and to identify response strategies to global environmental change based on assessment of options for mitigation and adaptation.

MAGNET uses information from IMAGE on land availability and suitability, on exogenous developments in crop and livestock production systems such as climate change impacts, and on agricultural expansion on heterogeneous land areas. The results from MAGNET on agricultural production and intensification/ extensification of crop and livestock production is used in IMAGE to calculate spatially explicit land-use change, and the environmental impacts on carbon, nutrient and water cycles, biodiversity, and climate. The Global Integrated Sustainability Model (GISMO) model quantifies changes in human development, including hunger and access to clean water and energy, and related impacts on human health (Lucas *et al* 2019), and is used in this paper to calculate the prevalence of undernourishment.

### 2.3. Food security indicators

To account for the various aspects of food security, we follow FAO's distinction of availability, access, utilisation and stability, and derive model-based indicators for the dimensions availability, access and utilization. These indicators have been developed and elaborated for the FOODSECURE scenarios (van Meijl *et al* 2020). Additionally, we apply a widely-used method to compute the prevalence of undernourishment, which is closely connected with food availability.

**Food availability** is measured by two indicators, 'food production' and 'food availability for consumption'. Food production is a crude indicator and indicates the total amount of food available in the various regions that is domestically produced (without international trade flows). To further explore the sources of future production increase, we decompose the change in food production into changes in agricultural area and yield increases. The second indicator, 'Food available for consumption', is measured in kcal per capita per day, and is a well-known and more precise indicator of food availability (e.g. Nelson *et al* 2013, von Lampe *et al* 2014). It includes all domestically produced and imported food available for consumption at household level, and thus includes also the food waste at household level. The indicator 'food available for consumption' is used as an input to the calculation of the prevalence of undernourishment.

**Prevalence of Undernourishment (PoU or risk of hunger)** measured in people at risk of hunger (millions) is based on the fraction of the population below a minimum level of dietary energy requirement and is used to monitor progress on SDG target 2.1 (end hunger by 2030). This indicator is directly related to food availability. The calculation of PoU is based on a method proposed by the FAO (2008b). The density function of dietary energy consumption is assumed to be lognormal with parameters  $\mu$  and  $\sigma$ , estimated on the basis of the mean dietary energy availability ( $x$ ) and the coefficient of variation (CV):

$$\sigma = \sqrt{\log(CV^2 + 1)}$$

and

$$\mu = \log(x) - \sigma^2/2.$$

The prevalence of undernourishment is then evaluated as follows:

$$PoU = \Phi[(\log(MDER) - \mu) / \sigma],$$

where  $\Phi$  is the standard normal cumulative distribution. The calorie-based food consumption (kcal/person/day) output from MAGNET was used as the mean dietary energy availability ( $x$ ). The minimum level of dietary energy requirement (MDER) is derived by aggregating the region-specific sex-age energy requirements weighted by the proportion of each sex and age group in the total population (FAO 2008b). The coefficient of variation (CV) is a function of per capita GDP as used in Hasegawa *et al* (2015), such that food distribution improves along with income growth.

$$CV = aGDP^b,$$

with optimistic estimates for the parameters  $a$  and  $b$  for SSP1 and SSP5, medium estimates for SSP2, and pessimistic estimates for SSP3 and SSP4 (See SI in Hasegawa *et al* 2015 for parametrisation).

**Food access** relates to people's food purchasing power and therefore to food prices, dietary patterns, and income developments (Lele *et al* 2016). First, we use the change in agri-food prices as a crude proxy for food access. This indicator neglects the income dimension of food access, but is used by many other studies. To account for the income dimension, we calculate the indicator 'food purchasing power', by relating price developments of a specific food consumption basket to income developments of a particular income group

Food Purchasing Power (% change) = % change in income of specific income group **minus** % change in the price of a food basket

For the food basket, we use consumption of cereals (rice and grains) as a proxy for the diet of people potentially in poverty, as rice is an important food component of poor people in Asia, while grains are important in Africa. We use changes in the wages of unskilled (production) workers in the cereals sector as a proxy for the income component of poor people.

For the food utilisation dimension less sophisticated proxies are used. **Food utilisation** is proxied by the fraction of calories derived from fruits and vegetables in total calories of food consumption, following for example FAO Compendium of indicators for nutrition-sensitive Agriculture (FAO 2016, FAO\WHO 1973, Lele *et al* 2016 and Shutes *et al* 2017).

## 2.4. Sensitivity to climate change impacts

By definition, the SSP scenarios do not include climate change impacts in order to facilitate consistent assessments of impacts and adaptation in follow-up research (Riahi *et al* 2017). However, as climate change impacts are considered a major threat to food security (UNFCCC, 2015, Mbow *et al* 2019) it is important to take the possible effects into account. As estimates of climate change impacts on crop yields vary widely (Rosenzweig *et al* 2014, Mbow *et al* 2019) we perform a sensitivity analysis for the Middle of the Road SSP2 scenario. We implement a high and a low climate change trajectory in line with RCP 6.0 and RCP 2.6, respectively (van Vuuren *et al* 2014). The climate change trajectories are implemented both with and without CO<sub>2</sub> fertilisation as this is considered a major uncertainty in the literature (Kolby Smith 2015) resulting in four sensitivity scenarios (RCP6.0-CO<sub>2</sub>, RCP2.6-CO<sub>2</sub>, RCP6.0-noCO<sub>2</sub>, RCP2.6-noCO<sub>2</sub>). The effects on crop yields are estimated using the IMAGE model which is dynamically coupled to the dynamic global vegetation model LPJmL. Regionally averaged yield shocks are subsequently implemented in MAGNET to estimate impacts on key variables for food security.

## 3. Results

In the presentation of the results, we focus on the global and regional trends within the various dimensions of food and nutrition security (section 3.2). First, in section 3.1, we describe and decompose the changes in agricultural production as these are important to understand the food security effects, and food production is also a crude indicator of food availability.

### 3.1. Agricultural production developments

Agricultural production is one of the indicators of food availability (section 2.3), and is in fact the basis for all food consumption and food security assessments. Therefore, we separately analyse food production, and also decompose how future increase in food production, required to feed the growing population, is achieved (table 3). Food production almost doubles in SSP5 (table 3) due to high demand for agricultural products caused by high income growth in this scenario (figure 1), higher level of food waste and high preferences for meat in diets (table 2). A similar production growth is observed in SSP3 due to similar factors as in SSP5 except that high population growth replaces the high income growth factor as important driver. Production growth is intermediate in the Middle of the Road scenario (SSP2) and low in SSP4 due to low economic growth. In SSP1 production growth is about half the growth observed in SSP5 and SSP3 due to less growth in demand for agricultural products due to lower population growth, reduction in food waste and diet shifts away from meat consumption.

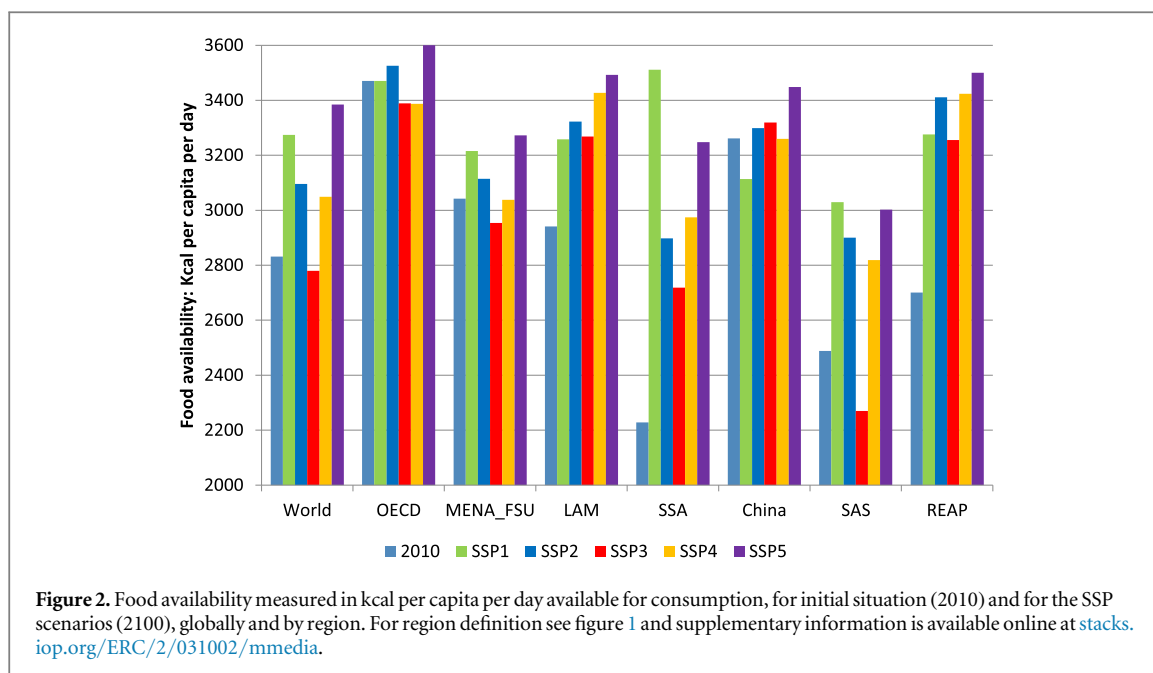
From the supply side, higher yields and land expansion lead to higher production. In the economic framework a part of the yields is exogenous and represents technological/genetic improvements in crop and livestock production systems, and a part is endogenous in the model determined by substitution effects among production factors (land, labour, capital, fertiliser, animal feed)<sup>4</sup>. The exogenous yield developments are based on a relation with GDP development (Doelman *et al* 2018), and show a range of 43%–56% globally, and

<sup>4</sup> If agricultural demand expands in land-scarce countries, land prices often rise faster than the price of labour and capital and farmers react by substituting the more expensive land with capital or labour and thereby increasing the yields above the trend. In land-abundant countries production expands mainly by using more land and land prices increase only a little, implying small substitution effects with labour and capital.



**Table 3.** Change in agricultural production (one of the food availability indicators) and its decomposition into production change through land-use change and through exogenous and endogenous yield change (% change 2010–2100, the change in production volume is the sum of changes in land demand and land productivities).

SSP	Indicator	World	OECD	FSU, Middle East, North Africa	Latin America	Sub-Saharan Africa	Rest of East Asia and Pacific	China	South Asia
SSP1	Production volume	45	−10	58	54	269	64	−18	75
	Land use area	−4	−13	−6	−8	11	−8	−11	−8
	Land productivity (exogenous)	50	24	44	31	116	55	6	56
	Land productivity (endogenous)	−2	−22	20	31	142	18	−13	27
SSP2	Production volume	72	17	109	94	278	83	6	86
	Land use area	8	−2	1	8	30	8	−5	5
	Land productivity (exogenous)	47	22	52	28	100	43	10	46
	Land productivity (endogenous)	17	−4	56	57	148	31	1	36
SSP3	Production volume	93	17	149	125	295	99	27	94
	Land use area	19	7	7	23	44	23	3	15
	Land productivity (exogenous)	45	11	56	32	95	37	8	39
	Land productivity (endogenous)	29	−1	86	70	156	39	16	40
SSP4	Production volume	59	8	101	74	271	70	−20	77
	Land use area	8	−8	−1	6	38	9	−7	7
	Land productivity (exogenous)	43	30	53	22	80	37	6	38
	Land productivity (endogenous)	8	−14	49	47	153	25	−18	31
SSP5	Production volume	96	66	128	142	280	88	20	91
	Land use area	11	5	2	16	29	8	−5	3
	Land productivity (exogenous)	56	30	57	33	118	49	9	51
	Land productivity (endogenous)	30	32	69	92	133	31	16	37



6%–118% on a regional scale. The endogenous yield developments vary more, and are in the range of –2% in SSP1 to 30% in the SSP5 globally, and –22%–165% on a regional scale. Due to low production growth and high exogenous yields, land prices increase less than wages and capital rents, leading to an additional endogenous extensification effect (–2%) in SSP1. The high production growth in SSP5 and SSP3 induce high levels of substitution as land becomes very scarce. Land prices increase a lot, even more than wages and capital rents, inducing producers to intensify production even more beyond the exogenous trend by using more labour and capital on their land. Sub-Saharan Africa stands out as endogenous additional yield effects are often as large or larger than the exogenous part. This indicates an enormous pressure on the land market and rising land and food prices given the high population and demand growth in these regions.

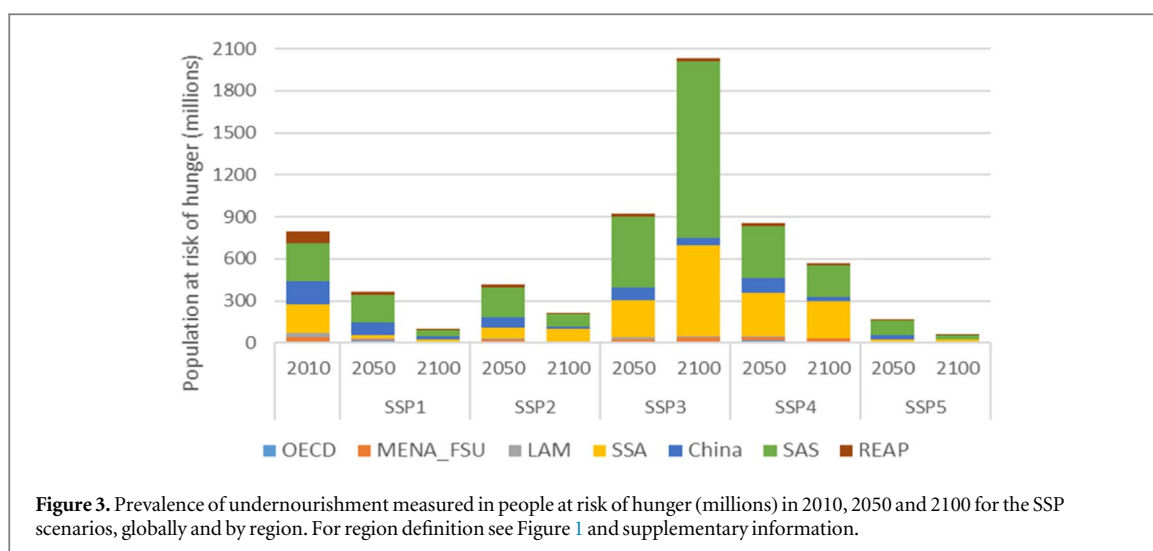
Land use developments differ substantially between the scenarios. Land use observes a reduction (–4%) in SSP1 due to lower production growth and increased environmental awareness, shows an intermediate increase of 8%–11% in SSP2, SSP4 and SSP5, and a high increase in SSP3 (19%). In SSP3 the increase is high due to a combination of no restrictions in the area of land use regulation, high population growth and low yield growth. Land use expands especially in Sub-Saharan Africa where the demand pressure is high and land for expansion is still available.

### 3.2. The various dimensions of food and nutrition security

#### 3.2.1. Food availability

We use ‘food production’ and ‘kcal per capita per day available for consumption’ as indicators of food availability. Food production is high in SSP5, SSP3, intermediate in SSP4 and SSP2 and low in SSP1 (see section 3.1 and table 3).

On the world level the food availability in terms of kcal per capita per day is a better indicator than food production as it takes energy content of food and population growth into account. This indicator gives a different picture as it increases substantially in both the SSP1 as well as the SSP5 worlds (figure 2). In SSP 5 the increase is observed in all regions due to high income growth and a high preference for animal products (especially in OECD countries). In the sustainability SSP1 scenario the increase in kcal per capita per day is high due to catching up in GDP per capita, especially in developing countries (very high in Sub-Saharan Africa (SSA) and to a lesser extent in the Rest of East Asia and Pacific region (REAP) and South Asia (SAS). In OECD countries food availability (which includes waste) is relatively low in SSP1 as waste is reduced and there is a negative preference shift for meat. Food availability in SSP1 in China (this region includes China, Mongolia, Taiwan and Hong Kong), with also a high initial level of food availability in 2010, is even lower as the diet shift to less animal meat is not matched by an even increase in the calories from crops. In the other regions that have a lower initial level of food availability or are more open in terms of trade (OECD) this is not the case. In the business as usual scenario (SSP2) and the inequality scenario (SSP4) kcal per capita per day increase moderately and there is a modest catching up of developing countries. However, in both scenario’s SSA is catching up much less than in the SSP1 and SSP5 scenarios. In the Fragmentation world (SSP3) food availability shows the least improvement



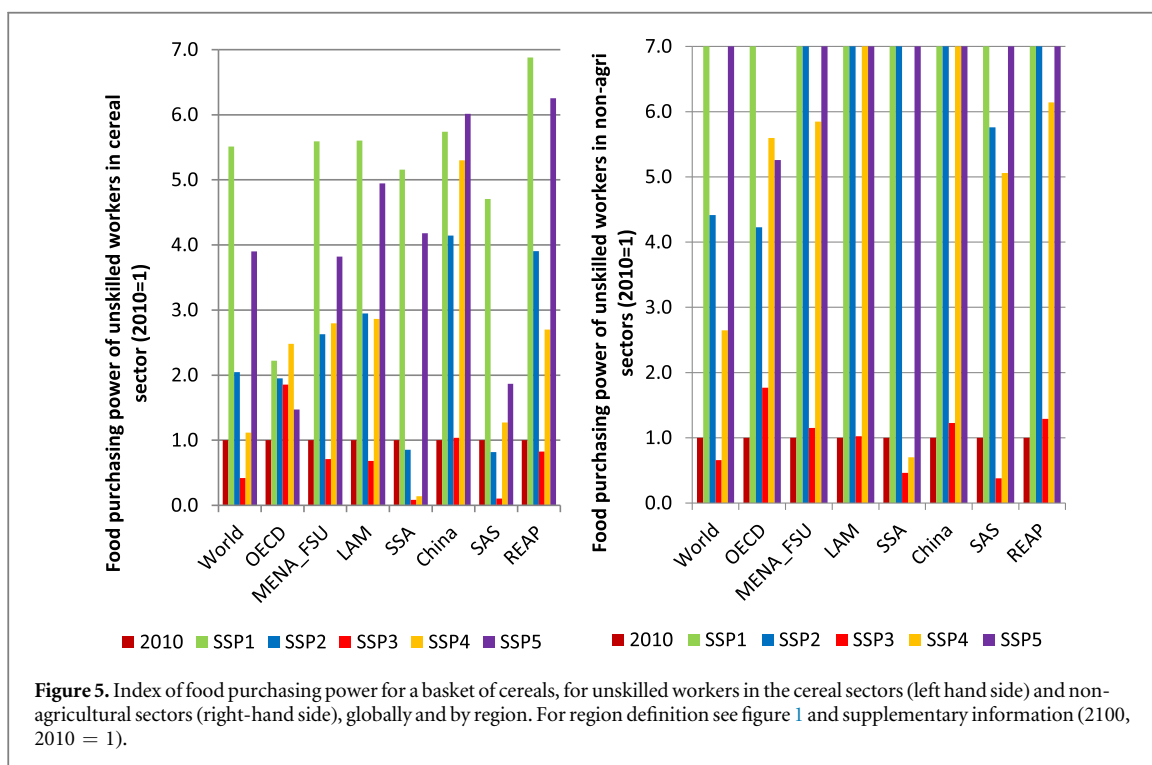
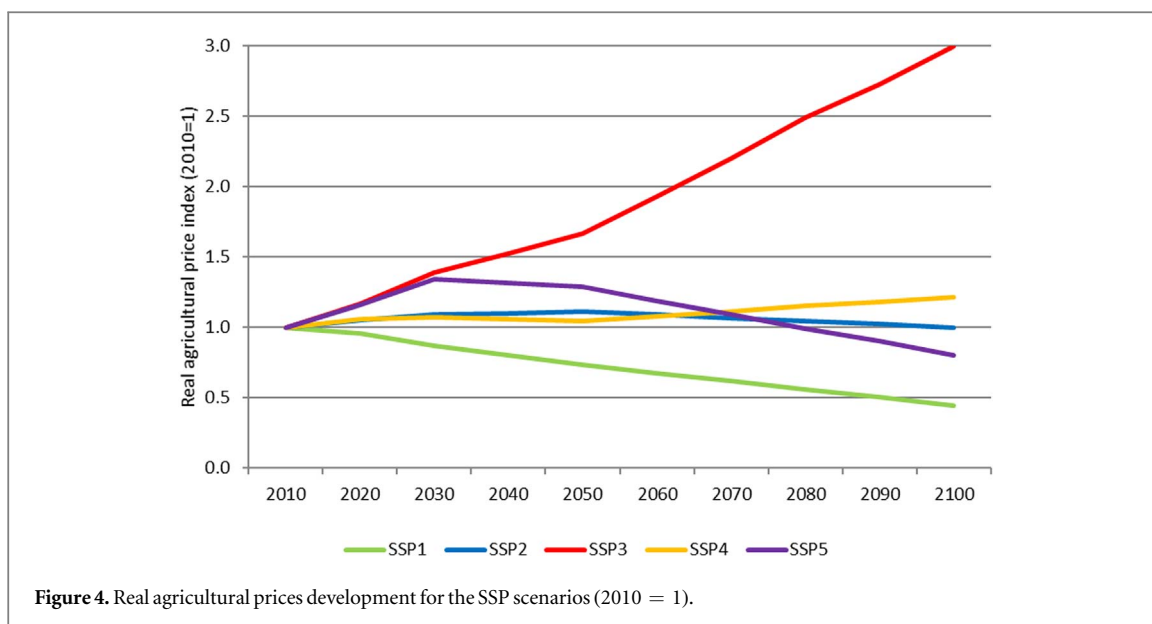
across all scenarios due to high population growth and income growth staying behind. It even deteriorates in the SAS region and there is less catching up in SSA. The decline in SAS is remarkable and caused by high demand growth due to high population growth and low supply growth due to low technological change in yields and labour productivity (implied by low GDP growth) in combination with land scarcity. This causes food prices to rise substantially and, due to relatively few international trade connections in the divided SSP3 world, the global market cannot mitigate this effect. The indicator ‘food available for consumption’ includes the food available at household level, and thus also includes household waste. As a result, assumptions on changes in household waste as in SSP3 and SSP5 also lead to a slight increase in this food availability indicator, but this effect is small compared to the other dynamics.

### 3.2.2. Prevalence of undernourishment

Figure 3 shows that, except for SSP3, towards 2100, the undernourished population decreases in all scenarios, becoming increasingly concentrated in SSA and SAS. Undernourishment is projected to be almost completely eradicated by 2100 in SSP5 and to a lesser extent also in SSP1. Large increases in food availability (kcal/cap/day), especially in SSA and SAS, together with low inequality and low population growth lead to this result. However, a small fraction of the population is still at risk of undernourishment, and thus also in an SSP1 world SDG2.1 is not met without additional policies. In contrast to this, in SSP3 global hunger increases from about 800 million people in 2050 to more than 2 billion in 2100, due to relative high inequality, and declining food availability in some regions, especially South Asia (see food availability section), which are mainly caused by slow GDP development and very high population growth. Improvements in food availability per capita in SSA cannot keep pace with increasing inequality, resulting in an increase from 200 million undernourished people in 2010, to 250 million in 2050 and 600 million in 2100. In SAS, decreasing food availability per capita (see food availability section) and increased inequality increase the undernourished population from 250 million in 2010 to 500 million and 1.3 billion in 2050 and 2100, respectively. Finally, global food availability is similar in SSP4 and SSP2, but due to higher inequality and population growth in SSP4 in SSA the prevalence of undernourishment is much higher.

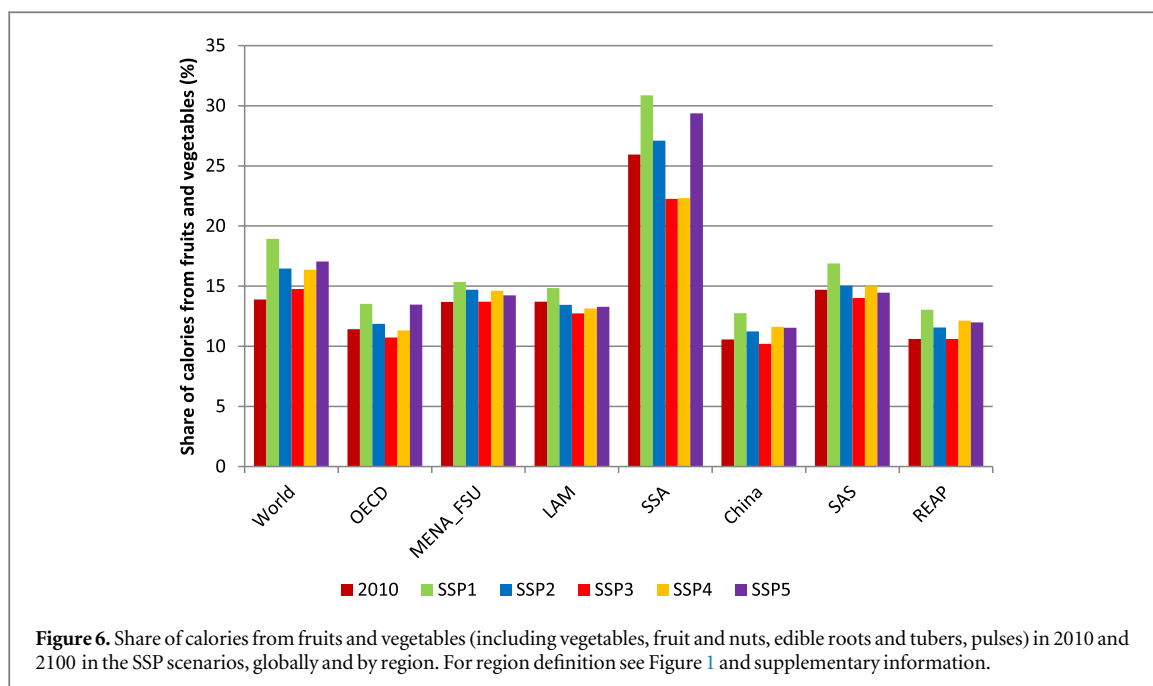
### 3.2.3. Food access

Agri-food prices decrease in SSP1 and are more or less stable in SSP2, SSP4 and SSP5. In SSP3 prices increase dramatically compared to 2010 (see figure 4). On the one hand, supply side factors such as exogenous yields and labour productivity growth, both driven by GDP, are lower in SSP3, inducing higher prices. Land availability is another supply factor as in the first half of the century land can expand in land-abundant countries, but when land also becomes scarce in these countries land prices start rising, causing food prices to increase further (especially in SSA). On the other hand, high population growth, increasing food waste and higher meat rich diets increase demand in SSP3, inducing higher prices. In the sustainable SSP1 scenario, food prices decrease as yields and labour productivity growth are high and demand growth is limited due to low population growth, waste reduction and preference shifts away from meat. SSP2 and SSP4 obtain more or less stable prices as supply drivers match demand drivers. SSP5 is interesting as, until 2030, agricultural prices increase and afterwards decrease. First, demand effects dominate as, in addition to the continued population growth, additional income has large food demand effects when income levels are relatively low. The decline in prices in subsequent periods



is caused by lower population growth and limited growth in food consumption as additional income does not lead to more food consumption when income is already high. These demand factors are reinforced by the supply side as labour productivity remains high, which is implied by high GDP growth.

Our second indicator for food access is the food purchasing power indicator of a basket of basic cereals for unskilled agricultural workers (figure 5, left-hand panel). Unskilled agricultural workers are proxied by unskilled workers in the cereal sector. This indicator shows large differences between the scenarios and also with the indicators related to food availability. This food purchasing indicator increases by 500% at the world level in the Sustainability world (SSP1) in the period from 2010 to 2100. The growth in developing countries (500%-700%) is much higher than in the OECD countries (200%). The pattern for the Fossil-Fuelled (SSP5) development is similar except at a lower level. In the Middle of the Road (SSP2) scenario, we see a different picture because at the global level the index only doubles, but decreases slightly for SSA and SAS. The decrease in SSA is interesting as other studies find that food insecurity disappears in SSP2 (see, e.g. Hasegawa *et al* 2015, Hasegawa *et al* 2018, Fujimori *et al* 2019). The decline in



food access for SSA in SSP2 is caused by rising cereal food prices (+60%) in SSA and a lower increase (+40%) in wages of unskilled agricultural workers, which together reduce the food purchasing power of these unskilled workers (the underlying cereal food price and wage developments are given in [appendix](#)). In the Inequality scenario (SSP4) the food purchasing power of unskilled agricultural workers strongly deteriorates in SSA. This feature spreads across the world in the Fragmentation (SSP3) scenario, leading to a global decline in food purchasing power for unskilled agricultural workers. A key mechanism for these developments is the segmented factor markets in MAGNET between agricultural and non-agricultural sectors implying that unskilled agricultural workers cannot easily move to other sectors in the economy. In the SSP3 we first see a strong increase in agricultural prices especially in developing countries (figure 4, regional detail in [appendix](#) table A1, A2 and A3). However, unskilled wages even decrease as (i) supply of agricultural unskilled workers grows quickly due to high population growth, (ii) demand for the agricultural sector grows slowly due to a relatively inelastic food demand, (iii) unskilled jobs can be relatively easily replaced by technical change (automation), and (iv) unskilled agricultural workers cannot move easily to non-agricultural sectors as they lack the educational requirements (lock-in effects). Inequality in terms of food access rises in the Inequality scenario (SSP4) in a few countries but in large parts of the world in the Fragmentation scenario (SSP3). In the Inequality SSP4 scenario, especially unskilled agricultural workers in SSA and SAS are left behind.

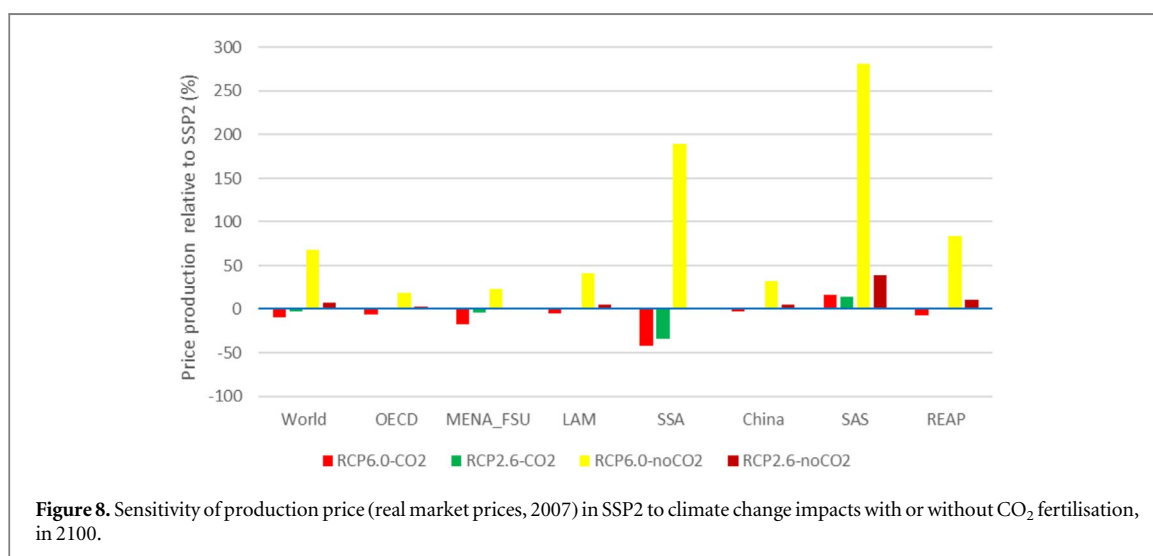
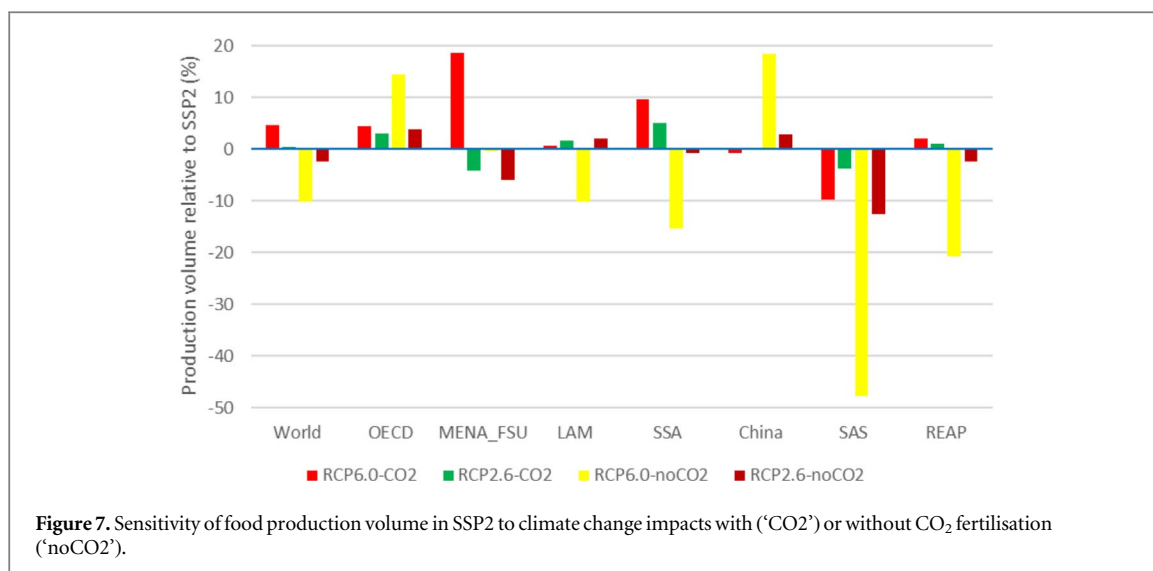
Food purchasing power for unskilled workers in non-agricultural sectors improves more than for agricultural workers (see right-hand side in figure 5). For SSP1, SSP5 and also SSP2 this indicator improves substantially within all countries, and at the global level it increases twice as fast as for agricultural workers, by a factor of 14, 9 and 4, respectively. SSP4 presents a very unequal world as this indicator increases by a factor of 5 across the world while it deteriorates in SSA, although the deterioration is much less than for non-agricultural workers. For SSP3 the food purchasing power for non-agricultural workers decreases at the global level, although the decrease is 50% less than for agricultural workers. The decline is also observed in fewer countries than for unskilled agricultural workers.

#### 3.2.4. Food utilisation

Dietary changes are a major vehicle for reducing micronutrient deficiencies and the burden of non-communicable diseases (Ruel 2003). Diet quality, as measured by the share of calories derived from fruit and vegetables, improves globally in all future worlds, and is driven mainly by income growth (see figure 6). The greatest improvements are seen in the Sustainability worlds (SSP1) and Fossil-Fuelled development (SSP5) where income per capita growth is highest. It is highest in SSP1 as people shift away from meat due to a scenario-specific preference away from animal products. The share of calories from fruits and vegetables is lowest in SSP3, where income per capita growth is lowest and people have a preference shift towards meat consumption.

### 3.3. Climate change sensitivity

The SSP2 scenarios including climate change impact show that RCP 2.6 has moderate impacts on agricultural production and food prices on the global scale, confirming that limiting global warming to 2 degrees mitigates



negative impacts on food security (figures 7 and 8). RCP 6.0 has a more substantial effect, with on average a positive impact when CO<sub>2</sub> fertilisation is included (+4% and -10% for agricultural production and food prices, respectively) and a strong negative impact when it is excluded (-11% and +65%). On the regional level the climate change impacts are stronger, most notably in SAS, where all RCP scenarios result in reduced agricultural production and increased food prices. This is due to strong increases in temperature leading to reduced yields, indicating that climate change might increase risks to food security in this already sensitive region. It must be noted though that a potential decrease in nutritional quality due to CO<sub>2</sub> fertilisation (Mbow *et al* 2019) is not taken into account.

#### 4. Discussion and conclusions

We have analysed possible long-term future developments of food and nutrition security, showing the policy gap between reference scenarios and achieving SDG2 on food security and malnutrition. A unique feature of this paper is that it focuses on three dimensions of food security within long-run SSP scenarios that are often used in the field of climate change. In addition to the often-quantified food availability indicators we focus especially on food access, which is more complicated as it needs information on income changes of income groups in addition to the price movements of their food diet. The MAGNET CGE model can contribute here, as for example wages of various factor types are endogenous. We included the characteristic that labour markets are segmented and that for example unskilled workers in the agricultural sector cannot move easily

to manufacturing and services sectors. This implies that certain labour skill types might be 'locked' in certain sectors that feature unfavourable conditions and these workers have to accept lower wages. In this paper diet changes to proxy food utilisation are only introduced in a crude way. Given the short-run features of food stability, this dimension is not taken into account in this medium- to long-term CGE model. In line with other studies we find that food availability, measured as kcal per capita per day, generally improves over time. Only in SSP3, food availability is projected to decrease in SAS due to high population growth and low supply side growth. As a result, the prevalence of undernourishment decreases in most scenarios, and hunger becomes increasingly concentrated in SSA and SAS. However, in contrast to other studies, we find that this hunger remains high in SSP4 (550 million people) and increases to over two billion people in SSP3 in 2050. The main reason for the difference is that in our SSP3 scenario land becomes increasingly scarce in SAS and to a lesser extent also in SSA. As a consequence, land and food prices increase significantly, decreasing the demand and thereby per capita food availability. In principle, increased trade would be a solution to limits in domestic production, but is difficult to achieve for regions with traditionally low involvement in global trade, like SAS. Food access, measured by a food purchasing power indicator of a basket of basic cereals for unskilled agricultural workers (proxied by unskilled workers in the cereal sectors), improves, although due to lock-in effects the wages of unskilled workers in agriculture might decline, leading to deteriorated food access in scenarios with high inequality (SSP4 and especially SSP3), but also in some cases in the business as usual scenario (SSP2). These findings are in line with, for example, the decrease in number of malnourished people from 1 billion to 800 million people on a global level in the period 1990–2015, whereas the number increased from 175 to 220 million in Sub-Saharan Africa (FAO 2015). Finally, our crude indicators of food utilisation and food stability indicate food security problems for SSA in SSP3 and SSP4.

This overall food security picture based on three dimensions of food security is less optimistic compared to previous studies. These studies only assessed food availability and risk of hunger and find an improvement of food security in most SSP scenarios (Hasegawa *et al* 2015, Bijl *et al* 2017, Hasegawa *et al* 2018, Fujimori *et al* 2019). The main reason for the difference with the findings of other studies is related to the modelling of agricultural land as our land supply curve implies a limited availability of potential agricultural land (i.e. the land asymptote). When countries come close to this asymptote due to demand growth then land prices and the related food prices will increase rapidly. In our SSP3 scenario land becomes increasingly scarce in SSA and especially SAS and land and food prices increase rapidly. The high food prices decrease the demand and therefore availability of food per capita.

Inclusive policies directed at investing in education and social security can prevent lock-in effects of unskilled workers in agriculture and is key to reverse these less optimistic findings and improve food access for more income groups. Efficient land use, knowledge and innovation policies are key for food availability, while nutrition, health and drinking water and sanitation policies could address food utilisation.

This study is a step towards including more food and nutrition security dimensions in long-term scenarios. There are a number of uncertainties and limitations to this work. Other studies have shown that global land-use models show a substantial range in projections of food availability, and results from the MAGNET model are characterised by median total and crop food availability, but relatively low livestock food availability (Stehfest *et al* 2019). The food demand of MAGNET is relatively inelastic in response to economic growth at high income levels as higher income does not lead to more food consumption. However, the substitution of basic commodities by more luxury commodities, above a certain calorie level, is low in the MAGNET model. Furthermore, MAGNET only models the increase in food availability, but not an increase of waste fractions at higher income levels, as suggested by e.g. Hiç *et al* 2016. Higher waste fractions are however part of the scenario assumptions (table 2). Overweight and obesity are increasingly relevant for food and nutrition security (Abarca-Gómez *et al* 2017). However, the prevalence of obesity is hard to model in long-term assessments, as it is more a social and cultural phenomenon than linked to economic processes as modelled here, and to our knowledge, no simplified modelling as in the case of risk of hunger (FAO 2008a, Hasegawa *et al* 2015) has been proposed yet.

The impact of climate change on crop yields and the agricultural system is large (Nelson *et al* 2013, Wiebe *et al* 2015), and has been explored here in a sensitivity analysis. Without effective CO<sub>2</sub> fertilisation, climate change impacts in RCP2.6, consistent with the 2 degree target, are small, but increase by several orders of magnitude in RCP6.0, especially in already vulnerable regions like SAS, SSA and REAP, but depend on the crop model and climate change pattern applied. Technological change, including yields and especially labour productivity, is key to all results but remains largely exogenous in this study while it should be treated endogenously. To better address food access, an explicit household dimension, covering both income and food expenditures at specific household level, is needed within the modelling framework. Crucial is the importance of transition possibilities of labour from agriculture to other sectors. Changes in the skill level and lock-in effects

are key for FNS and thus deserve more explicit attention in long-term projections than currently given in leading studies. For the food utilisation dimension the explicit modelling of micro and macronutrients at household level is needed in combination with clear guidelines of healthy diets. It is important to take into account the endogenous change in micronutrient content in food, either dilution due to climate change (e.g. Myers *et al* 2015, Smith and Myers 2018) or changes in germplasm (due to bio fortification) or industrial processing (i.e., fortification). For the stability dimension, long-term modelling has to be combined with processes and features of short-run dynamics, like variability in crop yields, prices and income. By combining long-term modelling with variability features it can be analysed how certain variabilities may play out differently in future socio-economic settings, e.g. under higher import-dependency. All these efforts are worthwhile as this study shows that food security is a complex problem that will not disappear automatically in the long run. Effective policies are needed to address the negative developments in all four dimensions of food security.

As the SDGs are gaining importance, also the number of model-based scenario studies on the SDGs, and thus also SDG2 ('end hunger'), is increasing. Therefore, a discussion is needed on the most suitable and sufficient indicators to model progress and risks towards achieving SDG2 in model-based assessments, and whether these studies should complement the official SDG indicator set (IAEG 2019) with indicators as suggested here to provide a broader picture of the underlying determinants of hunger. As mentioned by Pradhan (2019) 'the 2030 Agenda is much more than just a collection of goals, targets and indicators. Instead, SDGs are a system of interacting components'. A systemic approach is needed instead of looking at individual indicators, taking into account the interlinkages between SDGs and their targets. Furthermore, follow-up studies should explore possible policies to support food security targets, and their possible synergies and trade-offs with other SDGs to address the issue of food security in the much broader context of sustainable development.

### Annex: Key variables determining food access (food purchasing power) indicator

**Table A1.** Price of cereals (market prices) in 2100 (2010 = 1).

	World	OECD	MENA_FSU	LAM	SSA	China	SAS	REAP
SSP1	0.4	0.4	0.3	0.3	0.3	0.6	0.4	0.4
SSP2	1.0	0.8	0.7	0.6	1.6	0.8	1.5	0.7
SSP3	3.9	1.4	1.8	1.9	10.0	2.3	7.2	2.1
SSP4	1.5	0.7	0.6	0.6	4.8	0.7	1.1	0.8
SSP5	0.8	1.1	0.6	0.6	0.6	0.9	0.9	0.8

**Table A2.** Wage of unskilled labour in the cereal sector (nominal) in 2100 (2010 = 1).

	World	OECD	MENA_FSU	LAM	SSA	China	SAS	REAP
SSP1	2.0	1.0	1.8	1.7	1.4	3.3	1.7	3.0
SSP2	2.0	1.5	1.8	1.8	1.4	3.3	1.3	2.7
SSP3	1.6	2.5	1.3	1.3	0.8	2.4	0.7	1.7
SSP4	1.7	1.6	1.8	1.7	0.7	3.7	1.4	2.0
SSP5	3.1	1.5	2.4	2.8	2.4	5.2	1.7	4.9

**Table A3.** Wage of unskilled labour in non-agricultural sectors (nominal) in 2100 (2010 = 1).

	World	OECD	MENA_FSU	LAM	SSA	China	SAS	REAP
SSP1	5.1	3.6	5.7	6.8	18.5	7.2	12.3	8.9
SSP2	4.4	3.2	4.8	5.4	12.9	5.8	8.8	6.6
SSP3	2.6	2.4	2.1	1.9	4.6	2.8	2.7	2.7
SSP4	4.0	3.7	3.8	4.5	3.4	6.5	5.6	4.6
SSP5	7.4	5.5	9.1	10.8	33.8	10.2	20.2	13.4



## ORCID iDs

Hans van Meijl  <https://orcid.org/0000-0002-2455-6869>

Paul Lucas  <https://orcid.org/0000-0003-0292-7830>

## References

- Abarca-Gómez Leandra *et al* 2017 Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults *The Lancet* **390** December 16
- Armington P 1969 A theory of demand for products distinguished by place of production *International Monetary Fund Staff Papers*. **XVI** 159–78
- Barrett C 2010 Measuring food insecurity *Science* **327** 825–8
- Bijl D, Bogaart P, Dekker S, Stehfest E, de Vries B and van Vuuren D 2017 A physically-based model of long-term food demand *Global Environ. Change* **45** 47–62
- Bodirsky B L, Rolinski S, Biewald A, Weindl I, Popp A and Lotze-Campen H 2015 Global food demand scenarios for the 21st century *PLoS One* **10** e0139201
- Committee on World Food Security 2011 *Final Report* (Rome: Thirty-seventh session) 17–22 October 2011 ([http://fao.org/fileadmin/templates/cfs/Docs1011/CFS37/documents/CFS\\_37\\_Final\\_Report\\_FINAL.pdf](http://fao.org/fileadmin/templates/cfs/Docs1011/CFS37/documents/CFS_37_Final_Report_FINAL.pdf))
- Dellink R, Chateau J, Lanzi E and Magne B 2017 Long-term economic growth projections in the Shared Socioeconomic Pathways *Global Environ. Change* **42** 200–14
- van Dijk M and Meijerink G W 2014 A review of global food security scenario and assessment studies: Results, gaps and research priorities *Global Food Security* **3** 227–38
- Dixon P, van Meijl H, Rimmer M, Shutes L and Tabeau A 2016 RED versus REDD: Biofuel policy versus forest conservation *Economic Modelling* **52** 366–74
- Doelman J *et al* 2019 Making the Paris agreement climate targets consistent with food security objectives *Global Food Security* **23** 93–103
- Doelman J *et al* 2018 Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation *Global Environmental Change: Human and Policy Dimensions* **48** 119–135
- FAO 1998 *Rome Declaration on World Food Security and World Food Summit Plan of Action* (Rome: FAO)
- FAO 2008a *An Introduction to the Basic Concepts of Food Security* (Rome: FAO)
- FAO 2008b *FAO Methodology for the Measurement of Food Deprivation Updating the Minimum Dietary Energy Requirements* (Rome: FAO)
- FAO 2012 Coming to terms with terminology: food security, nutrition security, food security and nutrition and food and nutrition security *Committee on World Food Measuring Food Security and Nutrition: Technical Assessment and User's Guide Security (CFS) 39: 2012/4 Item V.a. Rome, Italy* 15–20 October (<http://fao.org/docrep/meeting/026/MD776E.pdf>)
- FAO 2015 *The State of Food Insecurity in the World* (Rome: FAO)
- FAO 2016 *Compendium of Indicators for Nutrition-Sensitive Agriculture* (Rome: FAO)
- FAO/WHO 1973 *Energy and protein requirements* (WHO technical report series No. 522 *FAO Nutrition Meetings Report Series No. 52*) (Geneva Switzerland: FAO/WHO)
- Fujimori S *et al* 2019 A multi-model assessment of food security implications of climate change mitigation *Nature Sustainability* **2** 386–96
- Godfray H, Beddington J, Crute I, Haddad L, Lawrence D, Muir J, Pretty J, Robinson S, Thomas S and Toulmin C 2010 Food Security: The Challenge of Feeding 9 Billion People *Science* **327** 812–8
- Hasegawa T *et al* 2015 Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways *Environ. Res. Lett.* **10** 1
- Hasegawa T *et al* 2018 Risk of increased food insecurity under stringent global climate change mitigation policy *Nat. Clim. Change* **8** Nature Publishing Group 699–703
- Hiç C, Rybski, D P and Kropp J P 2016 Food Surplus and Its Climate Burdens *Environ. Sci. Technol.* **50** 4269–77
- IAEG 2019 Internationally agreed methodology and guideline (<https://unstats.un.org/sdgs/iaeg-sdgs/>)
- IPCC 2019 Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, chapter 5
- De Janvry A, Fafchamps M and Sadoulet E 1991 Peasant household behaviour with missing markets: some paradoxes explained *Economic Journal* **101** 1400–17
- KC S and Lutz W 2017 The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100 *Global Environmental Change*. **42**
- Kolby Smith W 2015 Large divergence of satellite and Earth system model estimates of global terrestrial CO<sub>2</sub> fertilization *Nat. Clim. Change* **6** 7
- Kuiper M *et al* 2019 Labor supply assumptions—a missing link in food security projections *Global Food Security* **10** 328
- Lele U, Masters W A, Kinabo J, Meenakshi J V, Ramaswami B, Tagwireyi J, Bell W F L and Goswami S 2016 Measuring Food and Nutrition Security: An Independent Technical Assessment and User's Guide for Existing Indicators. Technical Working Group on Measuring Food and Nutrition Security ([http://fao.org/fileadmin/user\\_upload/fsin/docs/1\\_FSIN-TWG\\_UsersGuide\\_12June2016.compressed](http://fao.org/fileadmin/user_upload/fsin/docs/1_FSIN-TWG_UsersGuide_12June2016.compressed))
- Lucas P L, Hilderink H B M, Janssen P H M, KC S, van Vuuren D P and Niessen L 2019 Future impacts of environmental factors on achieving the SDG target on child mortality—A synergistic assessment *Global Environ. Change* **57** 101925
- Mbow C *et al* 2019 Food Security. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* ([https://ipcc.ch/site/assets/uploads/sites/4/2019/11/08\\_Chapter-5.pdf](https://ipcc.ch/site/assets/uploads/sites/4/2019/11/08_Chapter-5.pdf))
- Mukhopadhyay K, Thomassin P J and Zhang J 2018 Food security in China at 2050: a global CGE exercise *Economic Structures* **7** 1
- Müller C *et al* 2016 Drivers and patterns of land biosphere carbon balance reversal *Environ. Res. Lett.* **11**
- Myers S S, Wessells K R, Kloog I, Zanobetti A and Schwartz J 2015 Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modeling study *Lancet Glob. Health* **3** e639–45
- Nelson G *et al* 2013 Assessing uncertainty along the climate-crop-economy modeling chain *Proceedings of the National Academy of Sciences, USA* **111** 3274–9

- Nowicki P *et al* 2009 *Scenar 2020-II—Update of Analysis of Prospects in the Scenar 2020 Study—Contract No. 30—CE-0200286/00-21* (Brussels: European Commission)
- O'Neill B C *et al* 2012 *Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research* (Boulder, CO) November 2–4, 2011.
- O'Neill B C *et al* 2017 The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century *Global Environ. Change* **42** 169–80
- Pangaribowo E H, Gerber N and Torero M 2013 Food and Nutrition Security Indicators: A Review, *FOODSECURE working paper 05*
- Pradhan P 2019 Antagonists to meeting the 2030 Agenda *Nature Sustainability* **2** 171–2
- Pradhan P, Reusser D E and Kropp J P 2016 Correction: embodied greenhouse gas emissions in diets *PLoS One* **11** e0159285
- Riahi K, van Vuuren D P, Kriegler E, Edmonds J, O'Neill B C, Fujimori S, Bauer N, Calvin K, Dellink R and Fricko O 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Global Environ. Change* **42** 153–68
- Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *PNAS March* **4** 3268–73
- Ruel M T 2003 Operationalizing dietary diversity: a review of measurement issues and research priorities *J. Nutr.* **133** 3911S–26S
- Rutten M *et al* 2016 Metrics, models and foresight for European sustainable food and nutrition security: the vision of the SUSFANS project *Agric. Syst.* **163** 45–57 Available online 16 November.
- Shutes L *et al* 2017 Food and Nutrition Security and Sustainability in Long-Term Projections: An Assessment of the FoodSecure Scenarios. *FOODSECURE working paper no. 60*. The Hague.
- Smeets-Kristkova Z *et al* 2017 Assessing the impact of agricultural R&D investments on long-term projections of food security *Frontiers of Economics and Globalization* **17** 1–17
- Smith M R and Myers S S 2018 Impact of anthropogenic CO<sub>2</sub> emissions on global human nutrition *Nat. Clim. Change* **8** 834–9
- Stehfest E *et al* 2014 *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications* (The Hague: PBL Netherlands Environmental Assessment Agency)
- Stehfest E *et al* 2019 Key determinants of land-use projections *Nature Communication* **10** 2166
- Swinnen J F M 2011 The right price of food *Development Policy Review* **29** 667
- UN 2015 Transforming our world: the 2030 Agenda for Sustainable Development
- UNFCCC(United Nations Framework Convention on Climate Change) 2015 Adoption of the Paris Agreement. Proposal by the President (1/CP21) [cited 2016 02, Feb.] Available from: (<http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf>)
- van Meijl H *et al* 2018 Comparing impacts of climate change and mitigation on global agriculture by 2050 *Environ. Res. Lett.* **13** 064021
- van Meijl H, van Rheenen T, Tabeau A and Eickhout B 2006 The impact of different policy environments on land use in Europe *Agriculture, Ecosystems and Environment* **114** 21–38
- van Meijl H L, Shutes H, Valin E, Stehfest M, van Dijk M, Kuiper A, Tabeau W, van Zeist T, Hasegawa and Havlik P 2020 Modelling alternative futures of global food security: Insights from FOODSECURE, *Global Food Security*
- van Vuuren D *et al* 2014 A new scenario framework for Climate Change Research: scenario matrix architecture *Clim. Change* **122** 373–86
- van Vuuren D *et al* 2017 Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm *Global Environmental Change*, **42** 237–50
- von Lampe M *et al* 2014 Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison *Agricultural Economics* **45** 3–20
- Wiebe K *et al* 2015 Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios *Environmental Research Letters, ERL-100988* **10** 85010–24
- Woltjer G, Kuiper M, Kavallari A, van Meijl H, Powell J, Rutten M, Shutes L and Tabeau A 2014 *The MAGNET model - Module description. LEI Report 14-057* (The Hague: LEI - part of Wageningen UR (University & Research Centre))
- Worldbank 2017 Data (<http://data.worldbank.org/region/sub-saharan-africa>)