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LETTER

Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways

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Abstract

Shared socioeconomic pathways (SSPs) are being developed internationally for cross-sectoral assessments of climate change impacts, adaptation, and mitigation. These are five scenarios that include both qualitative and quantitative information for mitigation and adaptation challenges to climate change. In this study, we quantified scenarios for the risk of hunger in the 21st century using SSPs, and clarified elements that influence future hunger risk. There were two primary findings: (1) risk of hunger in the 21st-century greatly differed among five SSPs; and (2) population growth, improvement in the equality of food distribution within a country, and increases in food consumption mainly driven by income growth greatly influenced future hunger risk and were important elements in its long-term assessment.

1. Introduction

Models that integrate changing climate conditions with agricultural and economic models can assess the likely impact of climate change on future food supplies. However, although these studies are useful, they provide limited insight into understanding the future of food security, given that social welfare, distribution, political and institutional effectiveness, among other factors, come into play (Barrett 2010, Godfray *et al* 2010). Nelson *et al* (2010) found that (1) population and gross domestic product (GDP) were significant in determining the impact of climate change on food consumption and child malnutrition, and that (2) climate change would increase the number of malnourished children regardless of population and GDP assumptions, with the largest impact in low-income countries. Schmidhuber and Tubiello (2007) found that the impact of climate change strongly depended on population and GDP, and would be particularly serious in sub-Saharan Africa. However, these studies were based on the Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al* 2000) and past climate data (Meehl *et al* 2007), so impact assessments must be updated.

Hasegawa *et al* (2014) analyzed the effects of autonomous adaptations in crop production to reduce risk of hunger using the latest climate data (Taylor *et al* 2011) with a new scenario framework (introduced below). They found that these adaptations would reduce risk of hunger regardless of population, GDP, and climate conditions. While the above studies did not consider socioeconomic factors, van Ruijven *et al* (2014) showed that socioeconomic indicators should be considered, and expected that explicit treatment of these additional indicators would accelerate climate research. For example, Kii *et al* (2013) used inequality of domestic food distribution as a socioeconomic indicator when assessing food consumption. They found that average food consumption would be higher with lower inequality in food distribution.

A new, interdisciplinary scenario framework has recently been designed for climate change research (O’Neill *et al* 2014, van Vuuren *et al* 2014). It consists of two key elements: the magnitude and extent of climate change and climate policy (as characterized by the representative concentration pathways (RCPs)); and a set of alternative trajectories of future global development (described by shared socioeconomic pathways (SSPs)). The framework enables us to separate these elements to study the effects of climate polices. The SSPs focus on a specific component of future socioeconomic circumstances and therefore relay no explicit climate information. Recently, scenarios for various fields have been developed based on SSPs. For example, Hanasaki *et al* (2013a, 2013b) developed SSP-based water use scenarios and assessed global water stress and vulnerable regions. Undernourishment is one of the most serious issues related to food and agriculture, but there are no examples of hunger risk analyses in the 21st century consistent with SSPs.

In this study, we aim (1) to develop 21st-century scenarios for the risk of hunger consistent with SSPs as a baseline of climate impact research; and (2) to identify the elements that strongly influence future risk of hunger. Note that the scenarios developed here do not explicitly consider climate change impacts due to the definition of SSPs. In addition, although food security is multi-dimensional, this study focuses on risk of hunger and has its limits in representing various aspects of food security.

This paper is structured as follows. Section 2 presents a description of the approach and assumptions; section 3 describes 21st-century scenarios for the risk of hunger and the elements influencing them; and section 4 presents observations and conclusions.

2. Methodology

We developed five scenarios for the risk of hunger using SSPs. The Asia-Pacific Integrated Model CGE (AIM/CGE) was used to quantify qualitative SSP information. The elements (parameters) in the model related to food and hunger risk were assumed in a manner consistent with SSPs. Finally, a decomposition analysis was performed to identify elements that strongly influence future hunger risk. This analysis covers the period 2005–2100.

2.1. Shared socioeconomic pathways

O'Neill *et al* (2014) illustrate various futures for SSPs 1–5 in terms of challenges in mitigation and adaptation to climate change. Each SSP contains qualitative and quantitative information. SSP1, which describes 'sustainability', assumes low population growth and high economic growth. It also assumes high levels of education, governance, globalization, international cooperation, technological development, and environmental awareness. By contrast, SSP3, which describes 'fragmentation', assumes high population growth and low economic growth. It also assumes low levels of education and governance, regionalization, and low environmental awareness. SSP2 describes a 'middle-of-the-road' scenario between SSP1 and SSP3. In this study, SSP4, which assumes inequality, was interpreted such that optimistic scenarios like SSP1 are true for high-income countries, whereas pessimistic scenarios like SSP3 are true for low-income countries. Technology advances mainly in high-income countries, resulting in few mitigation challenges. In contrast, in low-income countries, poverty does not improve, and large numbers of people do not benefit from economic growth and remain vulnerable to climate change. SSP5 assumes low population growth, high economic growth, and high human development; however, environmental awareness is low, and there is a high degree of dependence on fossil fuels. Adaptations are easy to implement because of improved human capital in developing countries. SSPs 1 and 5 depict relatively optimistic scenarios with respect to hunger risk, whereas SSPs 3 and 4 depict relatively pessimistic scenarios. SSP2 falls between them.

2.2. Model

The AIM/CGE model builds on the work by Fujimori *et al* (in press) and Fujimori *et al* (2012), and has recently been used in several studies (Hasegawa *et al* 2014, Nelson *et al* 2014, von Lampe *et al* 2014). Supply, demand, trade, and investment are described in individual behavioral functions that respond to changes in the price of production factors and commodities as well as changes in technology. The functions also respond to preference parameters on the basis of assumed population, GDP, and consumer preferences. The supplementary material in chapter S3 provides details on the CGE model and parameter settings.

This paper focuses on the exogenous and endogenous responses of the model. Conceptually, a given population and income growth shift rightward the demand curve, increasing food demand and raising prices. Producers respond to the price increase by increasing production by expanding cultivated areas and pastures, and by increasing land productivity (production per unit land area) under a given land productivity and limited land. Consumers respond to the price increase by decreasing consumption, and shifting to less expensive goods. Some might face risk of hunger if they consume insufficient food. International trade globally reallocates production and consumption, decreasing the price of food and contributing to lower hunger risk. The CGE model covers the full economy and captures these general response options. Further details about model attribution are provided in Robinson *et al* (2014) and Valin *et al* (2014).

The population at risk of hunger is calculated outside the CGE model using the FAO approach (FAO 2008). Food consumption varies among households within a country and people who eat less than the minimum energy requirement face a risk of hunger. The CGE model calculated mean per-capita food consumption for a representative household. Then, the proportion of the population at risk of hunger was estimated from the mean per-capita food consumption, the minimum energy requirement, and the coefficient of variation (CV) of distribution of dietary energy consumption among households in a country (FAO 2008). Future changes in food distribution inequality were described by changing the CV and income growth. Future demographic changes were considered by calculating the mean minimum energy requirement of a country from its demographic structure (IIASA 2012) and minimum energy requirement by gender and age (FAO/WHO 1973). More details are provided in the supplementary material of chapter S1.

2.3. Future assumptions of relevant elements

Scenarios developed in this study were determined from the perspective of adaptation challenges because hunger risk is strongly related to these rather than mitigation challenges. Only elements related to hunger risk (i.e., meat diets) were used as parameters of the model (i.e., income elasticity of meat demand) (table 1). For population and income, we used SSP assumptions (IIASA 2012).

To make the scenario consistent with SSPs, optimistic, middle, and pessimistic assumptions for each parameter were determined from the adaptation viewpoint and then applied to SSPs 1–3. For SSP4, which describes an unequal scenario, optimistic, middle, and pessimistic assumptions were simply used for high-, middle- and low-income countries, although this allocation does not represent the poor living in high-income countries. For SSP5, with its low adaptation and high mitigation challenges, the optimistic assumptions of SSP1 with low adaptation challenges were applied for all elements except forest management. A parameter of forest management was assumed from the mitigation viewpoint because deforestation causes large emissions and forest protection is strongly related to mitigation.

Table 1 summarizes assumptions. Parameters were assumed based on observed statistics or future estimates of existing research. If neither were available, elements were simply assumed in a manner that is in line with SSPs storyline. Optimistic, middle, and pessimistic parameter values were set to express the range in observed data or existing research, if available. The assumption of income elasticity of meat demand is discussed below as an example. Assumptions for the other elements and explanatory figures can be found in the supplementary material.

Food consumption is calculated from income, food price, and the elasticity of food demand in the model. Income elasticity implicitly assumes an increase in food consumption and dietary changes with income growth and economic development. First, a function between per-capita meat consumption and income was estimated from national-level observed data, and used to assume a middle level of change in income elasticity of meat demand responding to income growth. Second, the function was shifted within the range of the observed data to elastic and inelastic directions of change in meat consumption against income growth. Then, these functions were used for both pessimistic and optimistic assumptions. High elasticity in income change, meaning a large increase in meat consumption with income growth, was used as a pessimistic assumption in terms of adaptation challenges. For crop products, no relationship was identified between crop consumption and income, so the values in Bruinsma (2006) were assumed to be constant for all SSPs. A rate of food loss is assumed to be constant at the current level.

2.4. Decomposition analysis

A decomposition analysis was performed to identify elements that strongly influence future hunger risk. The change in the population at risk of hunger from the base year was decomposed into four elements: population change, change in inequality of food distribution, change in food consumption, and trade. Further details of the decomposition analysis approach can be found in the supplementary material.

3. Results

3.1. Risk of hunger in the 21st century

We compared representative elements related to food (food consumption, population at risk of hunger, land use change, and crop price) among SSPs for an overview of developed scenarios (figure 1). An increase in food demand driven by population and income growth raised food price. Producers responded to the price increase by increasing production via increased cultivated areas and crop yields. Since growth yield and land capacity were limited, the large food demand was not met by production, resulting in a stable price increase, as shown in Nelson *et al* (2014).

Global food consumption increased from 2680 to 3270 kcal/person/day from 2005 to 2100 for SSP2, ranging from 2800 (SSP3) to 3510 kcal/person/day (SSP5). This trend was similar to that of income since changes in food consumption resulted primarily from changes in income (Hasegawa *et al* in review).

The global population at risk of hunger continued to decline through 2050 and was almost eliminated at the end of this century in SSPs 1, 2, and 5. Conversely, hunger risk remained in SSPs 3 and 4. In SSP4, which assumes inequality with little improvement in incomes of low-income countries, large populations at risk of hunger remained in these countries. In SSP3, the population began increasing around the 2030s, and began decreasing around the 2060s. (See section 3.4 for a decomposition analysis of this behavior.)

To meet the large food demand, SSP3 showed expansions of cropland and pastures, and a decrease in forests from 2005 to 2100, whereas SSP1 and SSP5 showed shrinking cropland and pastures, and stable

Table 1. Assumptions of SSPs.

Elements	Parameters	Data availability[a]	Optimistic/middle/pessimistic	Interpretation
Technological development	Irrigation growth Crop yield growth Land productivity of livestock products Land productivity of wood products	2 2 2 3	High/middle/low High/middle/low High/middle/low High/middle/low	High crop yield caused by irrigation expansion and high land productivity (production per unit area) for livestock and wood products decreased adaptation and mitigation challenges. High land productivity led to intensive use of land, a decrease in land demand, and an increase in land-based adaptive capacity for cropland expansion under climate change. It also decreased mitigation challenges by increasing land area for energy crop production and decreasing emissions from deforestation.
Equality of food distribution	Coefficient of variation of domestic distribution of dietary energy consumption within a country	1	Strong/middle/weak improvement	Inequality of food distribution increased adaptation challenges. Strong improvements in the equality of food distribution decreased hunger risk and vulnerability to climate change.
Forest management	Price elasticity of land use change	3	Low/middle/high	Forest management lowered mitigation challenges by decreasing deforestation and thus emissions. In the optimistic scenario with low price elasticity, strict forest regulation makes deforestation (and conversion) difficult, thus lowering emissions.
Meat diets	Income elasticity of meat consumption	1	Low/middle/high	A high meat diet increased challenges to both mitigation and adaptation. Consuming more meat led to an overall increase in food consumption, requiring larger areas of cropland and pastures, and causing a decrease in land-based adaptation. It also increased mitigation challenges by increasing emissions from livestock sectors and land conversion (Stehfest *et al* 2009).
International trade	Price elasticity of trade	3	Increase/unchanged/decrease	Globalization decreased adaptation challenges. International trade reallocated production and consumption, decreasing the price of food and contributing to a lower risk of hunger.

[a] 1: assumed based on observed statistics; 2: assumed based on future estimates of existing research; and 3: assumed in line with SSPs if information for 1 and 2 was not available.

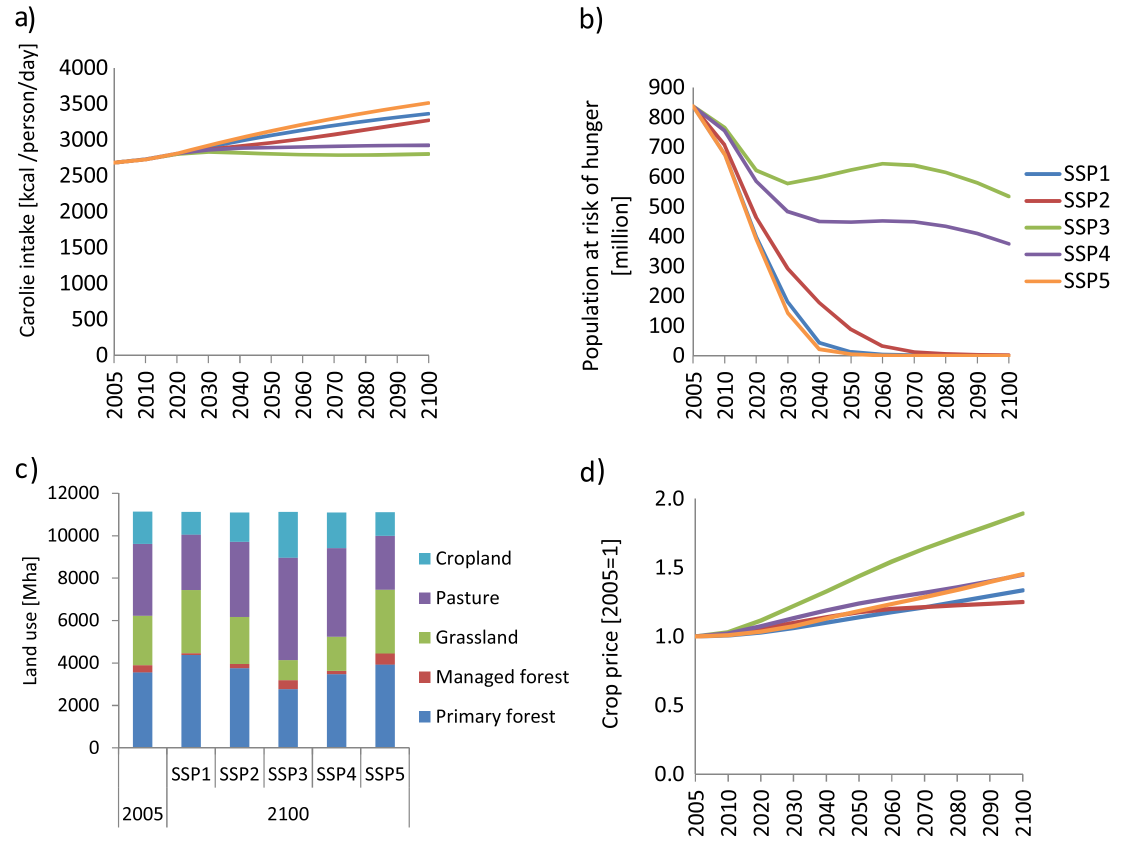

Figure 1. (a) Per-capita calorie intake; (b) population at risk of hunger; (c) land use change; and (d) average price of crops (rice, wheat, other cereal grains, oil crops, sugar crops and other crops), across SSPs estimated in this study.

forests. SSP3 assumes large population growth, a high increase in food demand, and low land productivity, resulting in expansions of cropland and pastures; SSP1 and SSP5 assume small population growth, low food demand, and high land productivity, resulting in contractions of cropland and pastures. Areas of cropland and pastures, in the main, did not change in SSP2.

World average prices of crops (rice, wheat, other cereal grains, oil crops, sugar crops and other crops) were estimated to increase by 2100 in all SSPs. SSP3 showed the highest increase and SSP2 the lowest. In SSP3, large population growth increased food demand, leading to an increase in the price of food. In SSPs 1 and 5, population decreases in China and Southeast Asia and low population growth in Africa in the latter half of this century caused tight labor markets and an increase in wages, resulting in rising food prices. In SSP2, supply and demand of food and labor markets were relatively balanced and the price of food increased less than in other SSPs. Explanatory figures of the price of food can be found in the supplementary material.

3.2. Comparison with existing studies

The range of estimates of populations at risk of hunger was more optimistic than in existing research (details in the supplementary material) see figure S12 in the supplementary material. In particular SSP 1, 2, and 5 values were below the range in existing research for all time periods. This may be because we took into account future improvements in food distribution equality, which was not the case for any existing research (Alexandratos and Bruinsma 2012). Their estimate of hunger risk was also relatively optimistic. Their estimate was larger than that of SSP2, presumably resulting from lower income assumptions. These findings indicate that inequality of food distribution influences long-term assessments of hunger risk.

3.3. Comparison with observed statistics

Observations of per-capita food consumption for the period 1980–2009 indicate sharp rises relative to income growth in low-income areas (less than US $10 000/person). Per-capita food consumption in high-income regions varied with a ceiling of 4000 kcal/person/day. Variations at high-income levels in observed data are evident in our estimates. Explanatory figures can be found in the supplementary material.

The same relationship was observed in per-capita meat consumption. Low-income areas experienced sharp growth relative to income growth, but there was more variation than that in total food consumption for all income ranges. This trend was also observed in our estimates. The income elasticity of meat is higher than that of crop-based foods, and regions which have

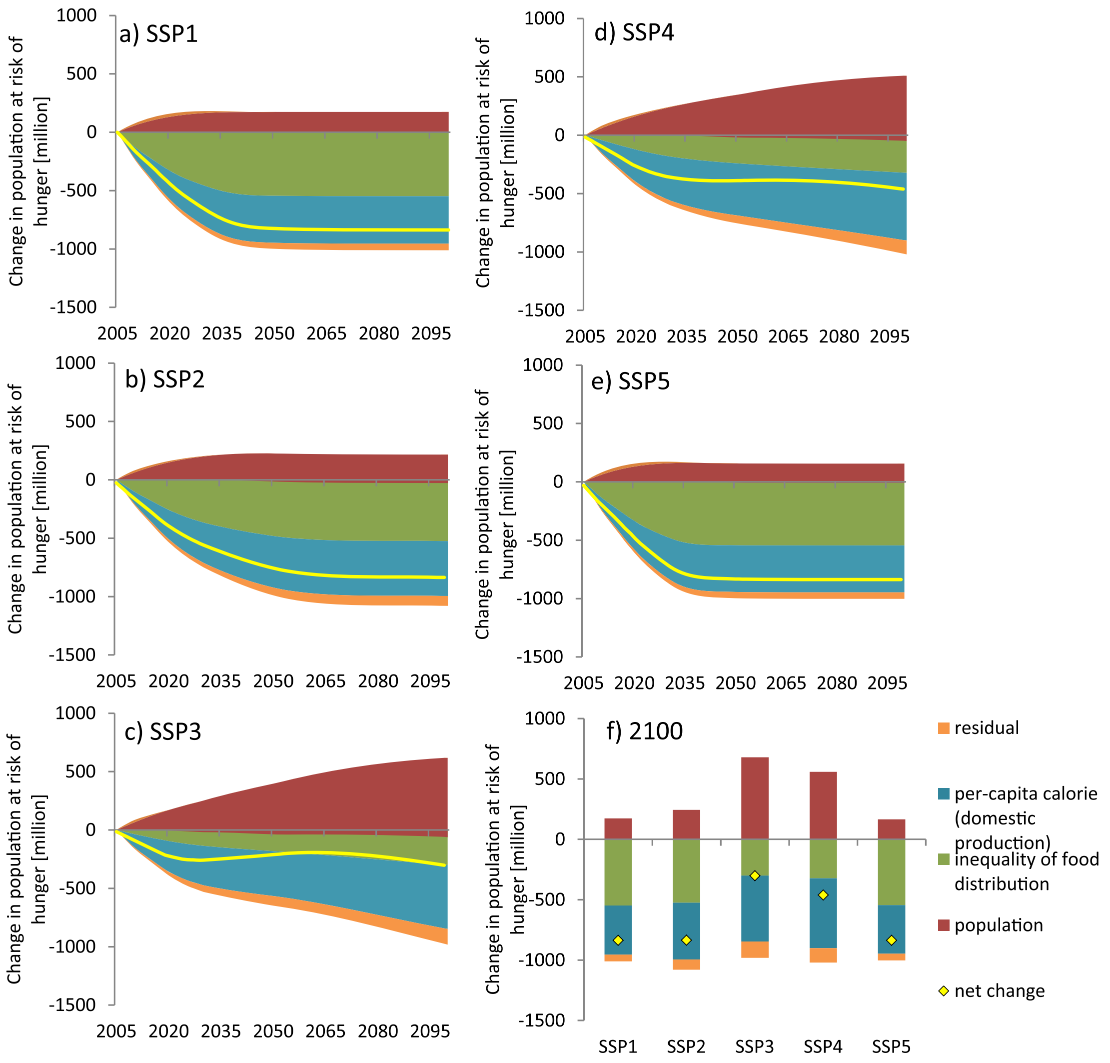

Figure 2. Cumulative changes in population at risk of hunger resulting from population, inequality of food distribution, and per-capita food consumption by 2100, relative to 2005. Change in per-capita food consumption due to trade is included in the residual.

a high income growth therefore experienced more drastic growth in meat consumption than growth in total food consumption.

3.4. Elements affecting hunger risk

Figure 2 (results of a decomposition analysis) shows the cumulative change in the population at risk of hunger caused by population, inequality of food distribution in a country, and per-capita food consumption by 2100, relative to 2005; (F) compares the cumulative change in 2100. This indicates that these three elements strongly influence future hunger risk and are largely different among SSPs. Population growth increased the risk of hunger while more equitable food distribution and increased food consumption decreased the risk. Population growth and inequality of food distribution were largely responsible for differences among SSPs in future hunger risk. The population growth increases the hunger risk strongly in SSPs 3 and 4 and less strongly in SSPs 1, 2 and 5. More equitable distribution of food decreases the risk strongly in SSPs 1, 2 and 5 and less strongly in SSPs 3 and 4. Increased food consumption largely decreases the risk in SSPs 3 and 4. This is because of a high increase in meat consumption relative to income growth.

Figure 3 shows (a) the regional population at risk of hunger in 2100 and (b) the cumulative change in the regional population in 2100 relative to 2005, under the most pessimistic scenario: SSP3. Here, per-capita calories were divided into domestic and imported food to observe contributions of trade changes. In 2100, the greatest hunger risk occurred in rest of Africa, India, and rest of Asia, accounting for >75% of the global population at risk. These three regions showed a large increase in hunger risk due to population growth. In contrast, China and Southeast Asia experienced a reduction in hunger risk primarily because of increased food consumption. Contributions of trade changes were small because future increases in food imports were limited. Food trade is based on the Armington assumption and the CES function. A share of domestic and imported commodities is unable to change drastically in response to price changes when the share parameter of the function is small. More

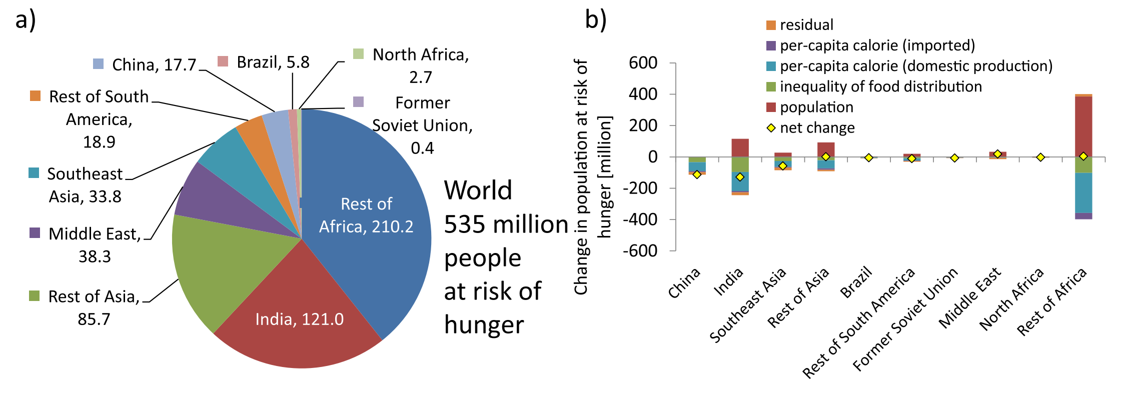

Figure 3. (a) The population at risk of hunger by region in 2100 for SSP3 (millions of people), and (b) cumulative changes in the regional population at risk of hunger caused by elements under SSP3 by 2100, relative to 2005.

details are provided in the supplementary material of chapter S6.

4. Conclusion and discussion

We developed scenarios for hunger risk in the 21st century using SSPs. Factors affecting future hunger risk were described within a range of existing research and observed data. We conclude from our analysis that:

- Risk of hunger without climate change in the 21st century differed among SSPs, resulting from the explicit use of a number of elements: population, GDP, inequality of food distribution among households within a country, demographic structure, crop yields, irrigation, and international trade. Elements that influenced the future reduction of hunger risk were population, inequality of food distribution, and per-capita food consumption. This may indicate that the secure access to food markets and increased food consumption for lower-income households that come with better domestic income distribution will be effective in reducing hunger risk.
- Scenarios for the risk of hunger in this study were more optimistic than those in existing research. One reason was the incorporation of improved equality of food distribution, which was not previously considered. This indicates that inequality of food distribution greatly influences long-term assessments of hunger risk. Inequality of food distribution could be interpreted as income inequality in hunger risk assessments, although no direct relationship has been established.

This study represents a starting point for research using SSP-based scenarios to predict risk of hunger in the 21st century. We hope that climate impact studies on agriculture will benefit from the scenarios in this study and will expand to include additional factors. We also hope that more specific and tailor-made scenarios of agriculture and food will be developed to aid policy decision-making, e.g., by assuming various elements based on the opinions of stakeholders. Note that although the scenarios developed here could be used for analyzing ranges of uncertainty (van Vuuren *et al* 2014), they should not be used for accurate predictions, and we cannot determine which is more correct. Thus, these scenarios still hold challenges, and are lacking in such factors as probabilities and systematic exploration of the large space of future possibilities (Morgan and Keith 2008).

Our study had some limitations that should be addressed in future research:

- Although food security is multi-dimensional, we were limited in representing various elements. For example, physical, social and economic factors affecting access to food were not explicitly represented although they were partly considered as inequality of food distribution, total factor productivity, and income elasticity of food demand. Other elements such as political instability, war, and conflict were not considered in this study.
- The range of optimistic and pessimistic values for individual elements may vary slightly among researchers creating the scenario. Thus, the range of hunger risk in this study may not be objective enough to be used globally. However, even if predictions are not accurate, our conclusions are valid.
- The study investigated socioeconomic developments and did not explicitly consider climate impacts as explained in the Introduction. Further analysis assuming climate impacts in a new scenario framework using SSPs and RCPs (van Vuuren *et al* 2014) may determine how climate outcomes vary among SSPs.
- The study aggregated the world into 17 regions to provide an overview of hunger risk among SSPs.

Regional downscaling could help clarify the spatial distribution of the impacts and provide additional useful information.

- This study only used one economic model, but more robust conclusions could be derived, or the scope of uncertainty could be identified, by estimating and comparing scenarios on the basis of multiple models. AgMIP (von Lampe *et al* 2014), for example, has analyzed climate change impacts on agriculture using multiple economic models. Applying common assumptions to models with different structures and parameters will clarify the range of future forecasts, an important direction for further investigation.

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