Title:

Risk of increased food insecurity under stringent global climate change mitigation policy

Authors:

Tomoko Hasegawa[1,2,*], Shinichiro Fujimori[1,2,3], Petr Havlík[2], Hugo Valin[2], Benjamin Leon Bodirsky[4], Jonathan C. Doelman[5], Thomas Fellmann[6], Page Kyle[7], Jason F. L. Koopman[8], Hermann Lotze-Campen[4,9], Daniel Mason-D'Croz[10,11], Yuki Ochi[12], Ignacio Pérez Domínguez[6], Elke Stehfest[5], Timothy B. Sulser[10], Andrzej Tabeau[8], Kiyoshi Takahashi[1], Jun'ya Takakura[1], Hans van Meijl[8], Willem-Jan van Zeist[5], Keith Wiebe[10], Peter Witzke[13]

Author Affiliations;

1. Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), 16–2 Onogawa, Tsukuba, Ibaraki 305–8506, Japan
2. International Institute for Applied System Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria
3. Department of Environmental Engineering, Graduate School of Engineering, Kyoto University, C1-3, Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto-shi, 615-8540, Japan.
4. Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg A 31, 14473, Potsdam, Germany
5. PBL Netherlands Environmental Assessment Agency, Postbus 30314, 2500 GH The Hague, The Netherlands
6. European Commission, Joint Research Centre, c/Inca Garcilaso 3, 41092 Seville, Spain
7. Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Court, Suite 3500, College Park, MD 20740, US
8. Wageningen Economic Research, Wageningen University and Research, 2585 DB The Hague, Netherlands
9. Humboldt-Universität zu Berlin, 10099 Berlin, Germany
10. International Food Policy Research Institute (IFPRI), 1201 I St. NW, Washington, DC 20005, USA
11. Commonwealth Scientific and Industrial Research Organisation (CSIRO), 306 Carmody Rd, St Lucia QLD 4067, Australia
12. E-Konzal Co. Ltd, 3-8-15, Nishinakajima, Yodogawa, Osaka, 532-0011, Japan
13. Institute for Food and Resource Economics, University of Bonn, Nussallee 21, D-53115 Bonn, Germany

* To whom correspondence should be addressed: hasegawa.tomoko@nies.go.jp

Introductory paragraph (150 words)

Food insecurity can be directly exacerbated by climate change due to crop production-related impacts of warmer and drier conditions expected in important agricultural regions[1, 2, 3]. However, efforts to mitigate climate change through comprehensive, economy-wide greenhouse gas emission reductions may also negatively affect food security, due to indirect impacts on prices and supplies of key agricultural commodities[4, 5, 6]. Here we conduct a multiple model assessment on the combined effects of climate change and climate mitigation efforts on agricultural commodity prices, dietary energy availability, and the population at risk of hunger. A robust finding is that by 2050, stringent climate mitigation policy, if implemented evenly across all sectors and regions, would have a greater negative impact on global hunger and food consumption than the direct impacts of climate change. The negative impacts would be most prevalent in vulnerable low-income regions such as Sub-Saharan Africa and South Asia, where food security problems are already acute.

Main texts (<2000words)

The Paris Agreement, adopted in 2015[7], calls for nations to limit global mean temperature rise well below 2 °C above pre-industrial levels by the end of this century, whilst pursuing efforts to limit warming to 1.5 °C. In the last decade, climate related policies have been implemented and have influenced not only greenhouse gas (GHG) emissions but also energy consumption and agricultural activities. For example, carbon taxes have been introduced in France, United Kingdom, Japan and some Canadian states; and some large agricultural producers such as the United States, Brazil, and EU countries have initiated ambitious biofuel policies in the form of tax exemptions or subsidies, or biofuel blending mandates[8], leading to the conversion of substantial amounts of crops into fuel. The ambitious GHG emissions mitigation objective of the Paris Agreement is expected to reduce the negative impacts of climate change on agriculture and food production, but may also lead to much larger scale bioenergy plantation expansion and afforestation. This would compete with land and freshwater requirements for food production, with a consequent risk of increasing food insecurity[4, 5, 6]. Moreover, since agricultural production is a primary source of income for many people in developing regions, climate change mitigation targeting emissions-intensive agricultural activities could also exacerbate rural poverty[9, 10].

Many studies have quantified the direct impacts of climate change on agricultural production[1], markets[2, 11, 12] and food security[3, 13, 14]. For example, a recent global agricultural economic model comparison study[2] found that future climate change lowers major crop yields by 17%, increases market prices by 20% and reduces related consumption by 3% by 2050, after adaptation of production across regions. Another integrated assessment of the impacts of emissions mitigation policies on the agricultural sector consistent with a 2 °C goal[15] shows that land-based mitigation efforts would increase food prices on average by 110% in 2100.

Here we present a model ensemble assessment of the combined effects of climate change impacts and emissions mitigation efforts on food security and hunger. We compare the results of eight global agricultural economic models (Table S 2) on a set of scenarios covering three dimensions: (1) selected “shared socio-economic pathways” (SSPs): “sustainability” (SSP1), “middle-of-the-road” (SSP2), and “regional-rivalry” (SSP3); (2) climate change impacts on crop yields corresponding to 2°C and 2.7°C increase by 2100 from the pre-industrial level (RCP2.6 and RCP6.0); and (3) climate change mitigation efforts: ambitious climate mitigation policies of a 2°C scenario (reducing emissions down to RCP2.6 emission levels) versus no climate action[6]. We also present a baseline scenario that assumes the current climatic conditions would prevail in the future (see Methods and Table S 1 for scenario architecture).

The selected scenarios allow us to verify the robustness of our results across a wide range of potential future socio-economic developments, to separate the pure effects of climate impacts and of ambitious mitigation efforts, and to keep consistency between severity of climate impacts and emissions mitigation levels in the different agricultural modelling frameworks. All of the models implemented emissions mitigation using a global uniform carbon tax on GHG emissions from different sectors (i.e., agriculture, land-use and/or non-agricultural sectors), the most standard approach in the literature[4, 5, 15, 16]. This uniform approach allows models to identify the most cost-efficient emissions pathway for a given climate target, and ensures the comparability of the results across modelling frameworks. Each model then shows specific endogenous responses, which include adjustments to production systems, technologies, and food demand and trade, among others. In all models, carbon prices lead to an increase in the cost of production and food prices through three main channels simultaneously: (1) the carbon tax on agricultural GHG emissions directly increases the production costs depending on the GHG intensity of the production[17]; (2) the carbon tax on the carbon emissions/sequestration associated with land-use change makes expansion of agricultural land more expensive and hence leads to higher land rents; (3) the carbon tax induces an increase in the biofuel demand from the energy system, which further increases the demands for land and hence again pushes the land rents upwards. The resulting increase in food commodity prices decreases food consumption or shifts demand to less expensive food products, with implications for the prevalence of hunger.

For the design of climate mitigation scenarios, only the most efficient emission abatement measures in the long run are considered. Although the implementation of short-term climate policies or current biofuel mandates is technically possible for the models, we do not explicitly consider these policies. For climate change impacts on crop yield, we selected results from five global climate models and three global crop models that were suitable for this study, and selected one global climate and crop model combination for each RCP and each assumption on CO_2 fertilization that is closest to the median at global aggregation[6]. CO_2 effects still has disputed impacts on food production as it increases biomass yields but decreases nutrient content. We assume similar to prior work[2] no CO_2 fertilization effect in the main scenarios (See Methods) but discuss the influence of varying this assumption for our results in Supplementary discussion S9.

Our analysis shows that by 2050, the potential for a sizeable increase in the risk of hunger is higher in the RCP2.6 scenarios under climate mitigation than in the RCP6.0 scenarios without mitigation in all socio-economic futures and economic models, despite the fact that RCP6.0 scenarios have more severe climate change and greater reductions in crop yields (Figure 1-c; Figure3a for regional information; Figure S 11). With the SSP2 socio-economic backdrop, the population at risk of hunger in 2050 increases by 24 million (2-56 million) with the climate impacts of the RCP6.0 scenario, compared with the baseline scenario. This number increases by around 78 million (0-170 million) people with the combined climate impacts and emissions mitigation policies of the RCP2.6 scenario (Figure 1a and Figure S 14 for the global and regional baseline scenario). Most of the increase in hunger in the RCP2.6 scenarios is caused by the implementation of climate mitigation policies, not the climate change impacts. Also for SSP2, average global caloric availability is lower by 45 kcal/person/day (2-68 kcal/person/day) under the RCP6.0 scenario compared to the baseline scenario, while the level is lower by 110 kcal/person/day (8-170 kcal/person/day) under the RCP2.6 scenario compared to the baseline scenario (Figure 1d; Figure 1b for baseline scenarios). These results imply that inclusive carbon taxation aimed at ambitious climate policy could significantly exacerbate food insecurity by 2050. Such policies increase food prices, decrease food consumption, and put more people at risk of hunger than in a future without these policies. Although changes in international commodity trade flows can help reallocate food from surplus to deficit countries, dampening the increases in food prices and risk of hunger, the adverse effects of mitigation efforts still remain. Our sensitivity analyses using the full range of the climate and crop models selected, with and without CO_2 fertilization effects, leads to similar observations (Supplementary discussion S8 and S9 with Figure S5 and S6 for the range of model selection and for CO_2 fertilization assumptions, respectively).

Figure 2 presents a more detailed analysis of food security implications using several different indicators. Mean dietary energy availability indicates food availability at an aggregated regional level while food prices, per-capita food expenditure, and the population at risk of hunger indicate food access[18]. Most models agree that mitigation policies linearly increase food prices and expenditure, decrease food availability, and increase the risk of hunger. Mitigation policies contribute to more than half of the overall price increases of crops and livestock products (Figure S 12). Particularly, the prices of the livestock products increase due to their comparatively higher GHG emission intensity and the higher prices of feed products and land rents both for pasture land and crop land. Price impacts and consequent consumption declines tend to be stronger for livestock products than for staple crops (Figure S 12, Figure S 13).

Regional estimates also deserve specific attention, considering the regional heterogeneity in climate change impacts and vulnerability. In Sub-Saharan Africa and South Asia (India and Other Asia; see Table S 4 for regional definitions), which currently already have the most acute prevalence of hunger (Figure S 14), the prevalence of undernourishment increases by 12 and 16 million people in 2050, respectively, on average, across all models in the RCP2.6 and SSP2 scenario (Figure 3a). These two regions account for 40% and 20%, respectively, of the global population at risk of hunger under climate mitigation in 2050. Moreover, most models show a great degree of price sensitivity of food demands in low-income regions, as compared with high-income ones (Figure 3b).

Our findings should not be interpreted to downplay the importance of future GHG emissions mitigation efforts, or to suggest that climate policy will cause more harm than good in general. Instead, this study highlights the need for careful design of emissions mitigation policies in upcoming decades, e.g. targeted schemes encouraging more productive and resilient agricultural production systems and the importance of incorporating complementary policies (e.g. safety-net programs) that compensate or counter-act the impacts of the climate change mitigation policies on vulnerable regions.

Moreover, climate policies can have synergistic effects with food security. For example, taxes on red-meat and dairy-products are expected to cut emissions and improve nutritional health[19]. Revenue from carbon taxes would bring a new source of income which could be used for food aid programs in low-income nations. Moreover, production systems in food insecure regions are often less GHG emissions and resource efficient than those in developed countries. For example, the developing world contributes 75% of global GHG emissions from ruminants while it supplies only half of milk and beef[20]. Thus, the transfer of resource-efficient production technologies, including land- and emissions-saving ones, to developing regions could both contribute to climate mitigation and economic development[4]. Combining climate policies with these other measures could promote food security and simultaneously reduce poverty and improve health conditions, increasing resilience of the food production systems to climate change and contributing to environmental sustainability.

Food security is a multi-dimensional and -disciplinary challenge, spanning scales from the global to local levels. In this study, we have focused on analyzing the potential consequences of climate change and emissions mitigation policies on two components of food security (food availability and food access) across an intersection of alternative futures in the socio-economic (SSPs), climate (RCPs), and mitigation policy spaces. We used a model ensemble to better assess the uncertainty inherent to the research questions addressed. Our analysis constitutes a first step to understanding important potential trade-offs between efforts to mitigate climate change and to reduce hunger, against a backdrop of a changing climate and dynamic socio-economic conditions.

While climate change is a global phenomenon, its specific impacts and efforts to mitigate its impacts will be realized at national and local levels. As such, future research will be required to assess the unique local and national challenges to adapting to and mitigating climate change while also reducing food insecurity. The multi-disciplinary framework which we have presented will also need to be further expanded to better assess changes to dietary quality and diversity, and their role in human health. Despite the need for further research, we believe this study helps improve understanding of the potential interactions between varied policy objectives within alternative climate, economic, and policy futures. In particular, it highlights the need for carefully designed mitigation policies for agriculture and land use, to ensure that progress towards climate stabilization and food security can be simultaneously achieved.

Figures

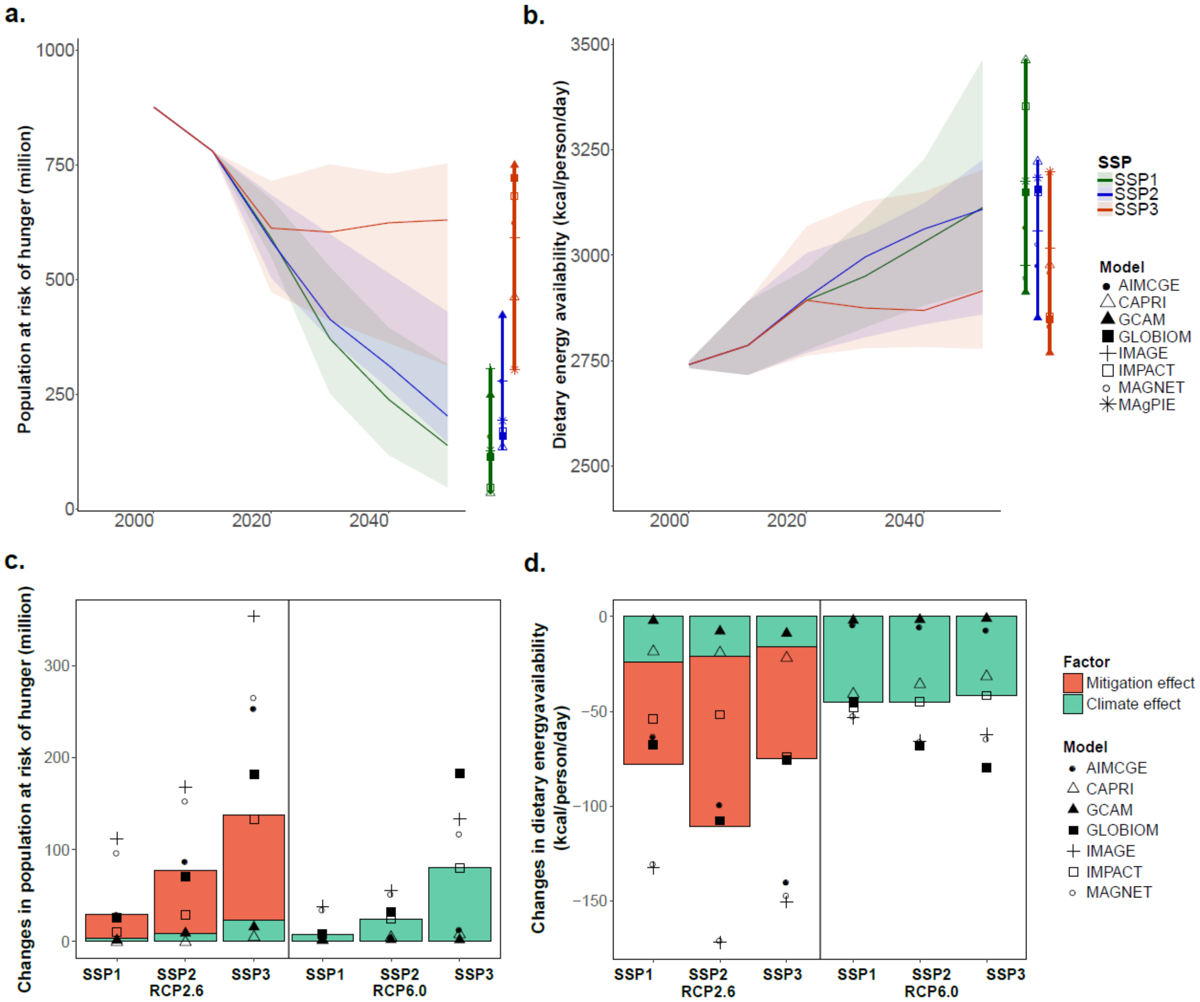

Figure 1 Effects of climate change and emissions mitigation efforts on food security. a) Global population at risk of hunger and b) global mean dietary energy availability in the baseline scenario under different socio-economic scenarios (SSPs). Ribbons and error bars show the ranges across models. c, d) Changes from the baseline level due to climate change and emissions mitigation efforts under different SSPs and climate change and emissions mitigation scenarios (RCPs) in 2050. Bars shows median level of individual effect across models. Symbols show the combined effects for each model. MAgPIE is excluded due to inelastic food demand.

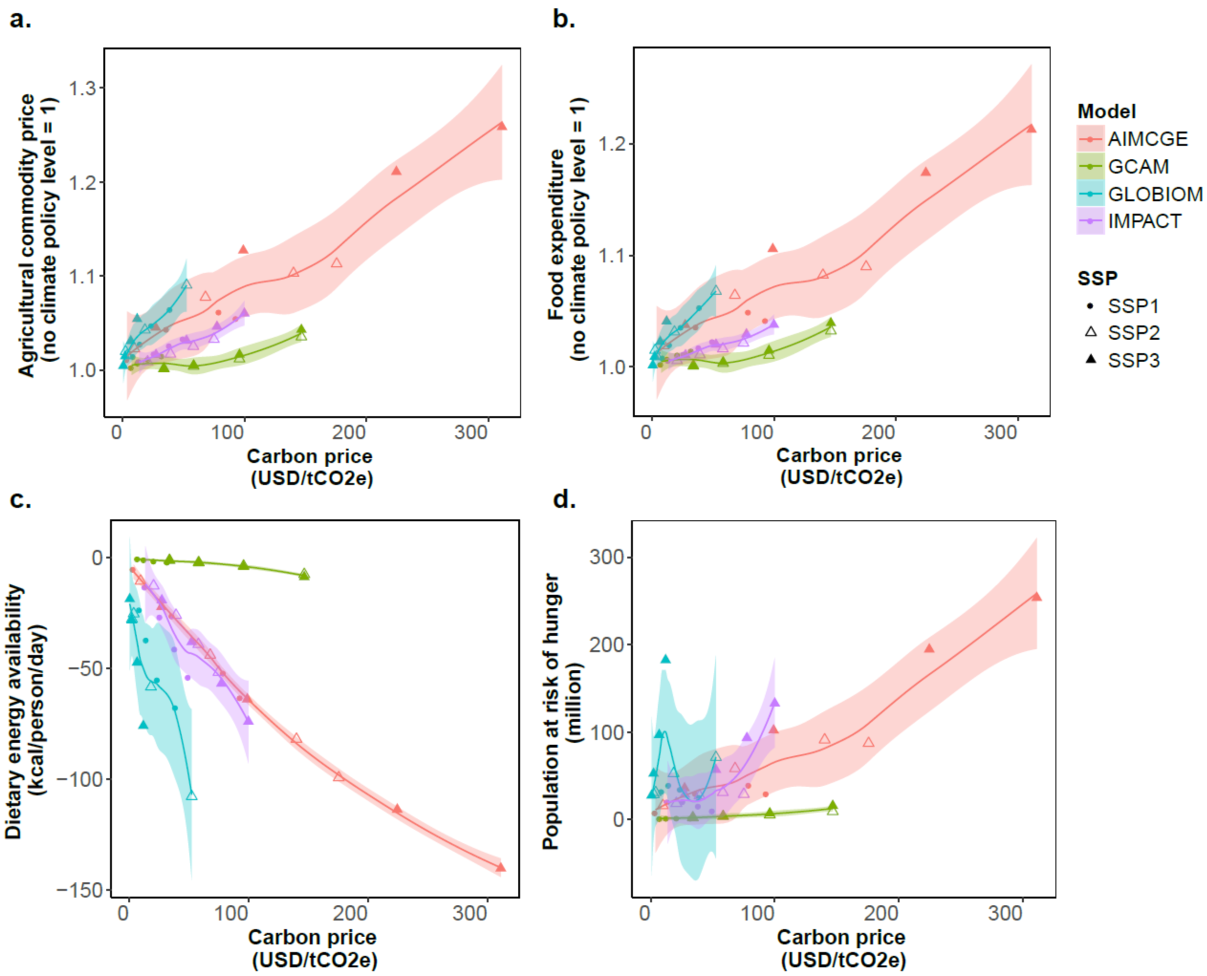

Figure 2 Relationship between land-based mitigation and food security indicators by 2050 under ambitious climate mitigation scenarios (RCP2.6) with residual climate change impacts for three SSPs. The range shows the 95% confidence level interval. This figure includes the model where carbon price is available.

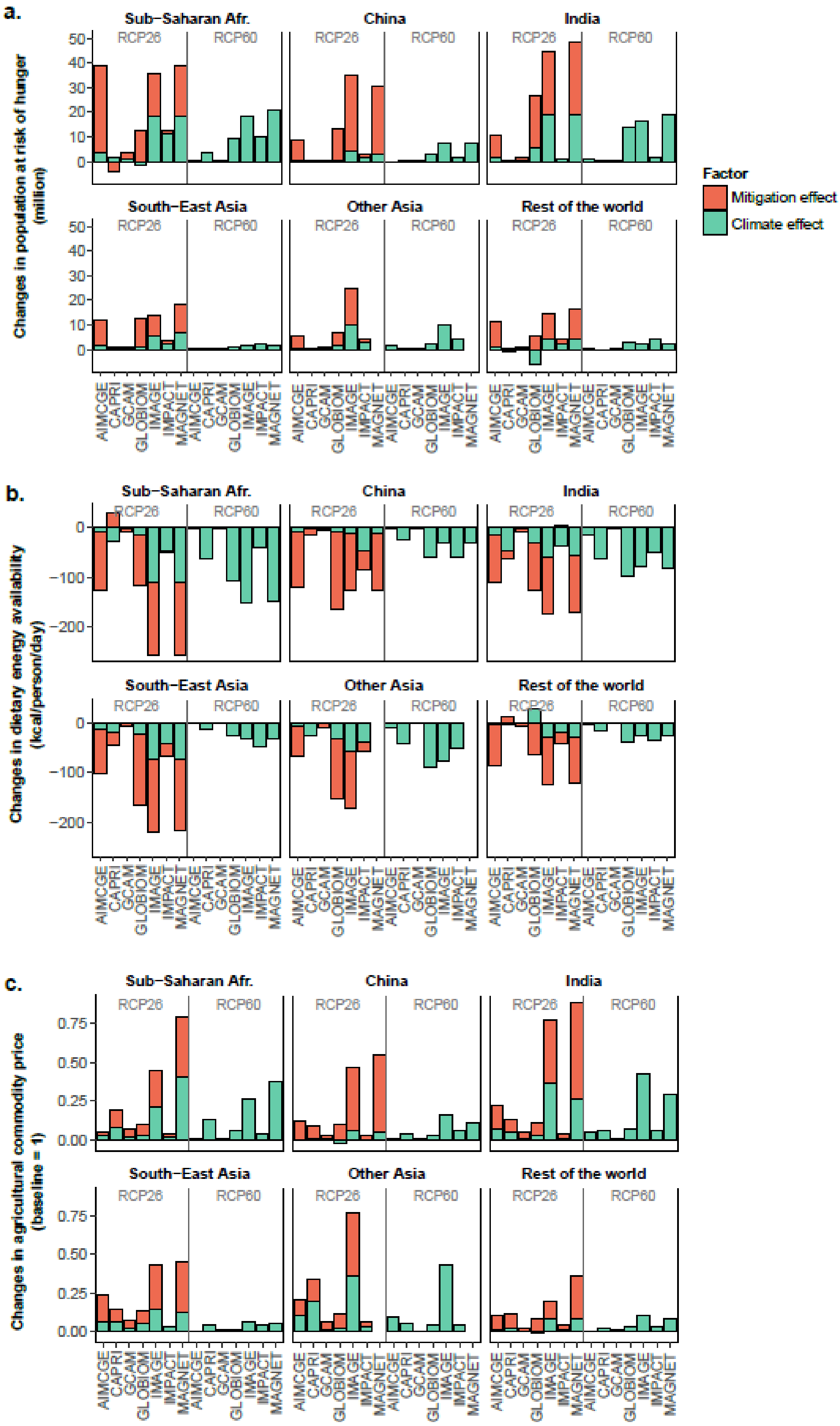

Figure 3 Regional effects of climate change and emissions mitigation on a) population at risk of hunger, b) mean dietary energy availability and c) agricultural commodity price in 2050 under intermediate socio-economic scenario (SSP2). Values indicate changes from the baseline scenario with no climate change and no climate mitigation. MAgPIE is excluded due to inelastic food demand. The value of India includes that of Other Asia in MAGNET.

References

1. Asseng S, Ewert F, Martre P, Rötter RP, Lobell DB, Cammarano D*, et al.* Rising temperatures reduce global wheat production. *Nature Climate Change* 2015, **5:** 5.

2. Nelson GC, Valin H, Sands RD, Havlík P, Ahammad H, Deryng D*, et al.* Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences* 2014, **111**(9)**:** 3274-3279.

3. Rosenzweig C, Parry ML. Potential impact of climate change on world food supply. *Nature* 1994, **367**(6459)**:** 6.

4. Havlík P, Valin H, Herrero M, Obersteiner M, Schmid E, Rufino MC*, et al.* Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences* 2014.

5. Hasegawa T, Fujimori S, Shin Y, Tanaka A, Takahashi K, Masui T. Consequence of Climate Mitigation on the Risk of Hunger. *Environmental Science & Technology* 2015, **49**(12)**:** 7245-7253.

6. Meijl Hv, Havlik P, Lotze-Campen H, Stehfest E, Witzke P, Domínguez IP*, et al.* Comparing impacts of climate change and mitigation on global agriculture by 2050. *Environmental Research Letters* 2018, **13**(6)**:** 064021.

7. UNFCCC. United Nations Framework Convention on Climate Change, 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. 2015.

8. REN21. Renewables 2007 Global Status Report (Paris: REN21 Secretariat and Washington, DC:Worldwatch Institute. : Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.; 2008.

9. Zekarias H, Thomas H, Alla G. Climate change mitigation policies and poverty in developing countries. *Environmental Research Letters* 2013, **8**(3)**:** 035009.

10. Hertel TW, Rosch SD. Climate Change, Agriculture, and Poverty. *Applied Economic Perspectives and Policy* 2010, **32**(3)**:** 355-385.

11. Lotze-Campen H, von Lampe M, Kyle P, Fujimori S, Havlik P, van Meijl H*, et al.* Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics* 2014, **45**(1)**:** 103-116.

12. von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, Calvin K*, et al.* Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics* 2014, **45**(1)**:** 3-20.

13. Baldos ULC, Hertel TW. Global food security in 2050: the role of agricultural productivity and climate change. *Australian Journal of Agricultural and Resource Economics* 2014, **58**(4)**:** 554-570.

14. Hasegawa T, Fujimori S, Shin Y, Takahashi K, Masui T, Tanaka A. Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. *Environmental Science & Technology* 2014, **48**(1)**:** 438-445.

15. Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E*, et al.* Land-use futures in the shared socio-economic pathways. *Global Environmental Change* 2017, **42:** 331-345.

16. Popp A, Rose SK, Calvin K, Van Vuuren DP, Dietrich JP, Wise M*, et al.* Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change* 2014, **123**(3)**:** 495-509.

17. Frank S, Havlík P, Soussana J-F, Levesque A, Valin H, Wollenberg E*, et al.* Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters* 2017, **12**(10)**:** 105004.

18. FAO. Food security indicators. In: FAO, editor. Rome, Italy; 2016.

19. Springmann M, Mason-D/'Croz D, Robinson S, Wiebe K, Godfray HCJ, Rayner M*, et al.* Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Clim Change* 2017, **7**(1)**:** 69-74.

20. Herrero M, Havlík P, Valin H, Notenbaert A, Rufino MC, Thornton PK*, et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences* 2013, **110**(52)**:** 20888-20893.

Corresponding author

Correspondence and requests for materials should be addressed to T.H.

Acknowledgments

T.H., S.F., K.T. and J.T. acknowledge support from the Environment Research and Technology Development Fund 2-1702 of the Environmental Restoration and Conservation Agency of Japan and the JSPS Overseas Research Fellowships. P.H., H.V. A.T. and H.v.M. acknowledge support from the European Union's Horizon 2020 research and innovation programme (EU H2020) under grant agreement no. 633692 (SUSFANS project). B.L.B. acknowledges support from the EU H2020 under grant agreement no. 689150 (SIM4NEXUS project). K.W., T.B.S., and D.M.D. acknowledge support from the CGIAR Research Programs on Policies, Institutions, and Markets (PIM) and on Climate Change, Agriculture and Food Security (CCAFS). This study has been partly funded by the Joint Research Centre of the European Commission (AGCLIM50 Project).

Author Contributions

T.H. coordinated the conception and writing of the paper, performed the scenario analysis and created the figures; T.H., S.F, Y.O. created the hunger estimation tool for the multiple models; T.H., S.F, P.H. and H.V. designed the research, led the writing of the paper and designed the scenario settings, which were developed and contributed by H.L.C., I.P.D. and H.v.M., with notable contributions from T.H., S.F., K.T., J.T. (AIM/CGE), P.H., H.V. (GLOBIOM), T.F., I.P.D., P.W. (CAPRI), P.K. (GCAM), J.C.D., E.S., W.J.v.Z. (IMAGE), D.M.D, T.B.S, K.W. (IMPACT), J.K., A.T., H.v.M. (MAGNET), B.L.B. and H.L.C. (MAgPIE); all authors provided feedback and contributed to writing the paper.

Competing interests

The authors have declared that no competing interests exist.

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission or the other institutions involved.

Data availability

Scenario data for all the scenarios will be made accessible online via the repository: http://data.europa.eu/89h/b6722b2e-483b-4f2e-ab45-4eb518939134.

Methods

We used eight agricultural economic models or integrated assessment models (IAMs) which sufficiently represent agricultural market and land use to assess the interaction between food security and climate change impact and mitigation. All of the food-related indicators shown in the main text are direct outputs from the models except the population at risk of hunger.

Here, we give scenario settings, data used for scenario runs, model representation of climate policy, and the method to project to population at risk of hunger.

Scenario settings

To quantify the effects of climate change and mitigation, we develop a set of 12 scenarios combining three socioeconomic conditions and four climate change and climate policy dimensions including a baseline scenario that assumed current climatic conditions would prevail in the future (i.e., NoCC) as shown in Table S1. For the socio-economic assumptions, we used three Shared Socio-economic Pathways (SSPs) describing “sustainability” (SSP1), “middle of the road” (SSP2), and “regional rivalry” (SSP3) pathways to address the uncertainty of socioeconomic conditions. The SSPs are being developed internationally to perform cross-sectoral assessments of climate change impact, adaptation, and mitigation[21].

The SSPs are representative future scenarios, including both qualitative and quantitative information in terms of challenges in mitigation and adaptation to climate change. For climate change and climate policy dimensions, we utilize four cases: a baseline scenario with no climate changes (NoCC), a climate change scenario where the climate impacts from RCP6.0 was implemented, and climate mitigation scenarios without and with residual climate change impacts. The comparison between baseline and climate change scenarios allows to extract the pure climate change effects ("Climate effect" in RCP6.0). The difference between scenarios with and without climate policy allows assessment of the effects of ambitious climate policy ("Mitigation effect" of RCP2.6). Comparing scenarios with and without the residual climate effects under climate mitigation allows analysis of the pure residual climate impacts effects on agriculture at 2°C of warming ("Climate effect" of RCP2.6). For climate condition, we harmonized the exogenous climate impacts on agricultural productivity by using crop yield data under two Representative Concentration Pathways (RCPs) [the intermediate climate change pathway (RCP6.0; 2.7°C increase from the pre-industrial level) and the carbon constrained pathway (RCP2.6) which is often interpreted as a 2°C goal in line with the Paris Agreement[7] to achieve more than 66% chance to stay below 2.0°C]. RCP2.6 and RCP6.0 are the GHG concentration pathways stabilizing radiative forcing at the end of the 21st century at approximately 2.6 and 6.0 W/m^2, respectively[22, 23]. RCP2.6 corresponds roughly to a global mean temperature rise from preindustrial times to less than 2°C by 2100 while RCP6.0 has a 2.7°C rise. In the SSP scenarios[24], most models' reference scenarios had forcing levels in 2100 of around 7 W/m^2. Thus, while no-mitigation scenarios are generally between RCP6.0 and RCP8.5, here we have selected RCP6.0 because it is relatively closer to 7 W/m^2.

Socioeconomic assumptions and data.

Each model changes socio-economic assumptions such as population, gross domestic product (GDP), dietary preferences, agricultural intensification irrespective of climate change, land-use regulation and international trade according to the SSP storylines[15]. All models were run with exogenous GDP and population, which were harmonized across models using the SSP socio-economic data[25]. In SSP2, the global population reaches 9.3 billion by 2050, an increase of 35% relative to 2010, and global GDP triples. For other characteristics captured by SSPs, the modeling teams made their own assumptions on how to best represent the described future trends. It is expected that model results for the same scenario will differ significantly, due to different interpretations and implementations of the SSP storylines across models. The effectiveness of agricultural technologies (e.g., improved crops, irrigation expansion, changes in trade) and other socio-economic conditions (e.g., population growth and income) can be assessed by comparing results across the SSPs. The models implicitly assume present-day agricultural policies to remain in place through calibration (e.g., price wedges based on statistical data[12]). Although all of the current national agricultural policies and governmental actions were implicitly covered, some of the specific features of these policies, going beyond the relative price difference were not captured. There are some studies considering the current short-term climate targets (e.g. the Nationally determined contributions (NDCs))[26, 27] or the biofuel policies or mandates (e.g. the U.S. renewable fuel standard (RFS2) or European Union renewable energy targets in the Renewable Energy Directive (RED))[28, 29, 30, 31]. Although the implementation of these policies is technically possible for the models used in this study, here we focus on the implications of climate change and emissions mitigation for food security and do not explicitly consider these policies. More detailed descriptions of the individual models can be found in each model paper shown in Table S 2.

Climate change effects on crop yield

In the scenarios with climate change, we used results of the yield change of up to twelve types of crops (maize, millet, rice, wheat, rapeseed, soybeans, sunflower, other oilseeds, cassava, ground nuts, sugar beet and sugar cane) estimated by using the five global earth system or climate models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M) contributing to the fifth phase of the Coupled Model Intercomparison Project (CMIP5)[32], and three global crop models (EPIC[33], LPJmL[34, 35], pDSSAT[36, 37]) that contributed to the ISI-MIP fast-track data archive[38]. These three crop models were selected according to data availability of at least four major crop types (rice, wheat, maize, and soybean) for both RCP2.6 and RCP6.0 with and without assuming CO_2 fertilization effects. For the mapping of crops simulated in the crop models to commodities used in the economic models, we apply the same methods as prior AgMIP research[2] (Table S5). For crops where yield impact data are not available, we used the average yield impacts of the crops with available data (see Table S5). To input the grid-based yield information into the global models, the gridded yields were spatially aggregated into country or regional values using the present crop- and irrigation system specific areas based on the Spatial Production Allocation Model (SPAM) data base[39]. Direct climate change impacts on livestock and fish production are not considered due to data limitation. Since the portion of the global population that is most vulnerable to food security issues tend to rely mostly on crops for food, this assumption would likely not affect change our findings, but further analysis would be required for confirmation.

Model representation of climate policy

All models implemented a global uniform carbon price on greenhouse gas emissions across sectors in order to represent ambitious mitigation measures. The uniform carbon price ensures cost-effective achievement of emission reduction, but does not necessarily minimize food security. In the models, the carbon price leads to an increase in the cost of production and then food price through three channels: (1) putting carbon taxes on agricultural GHG emissions directly increases the costs of production proportional to the GHG intensity of the production[17], and therefore food prices; (2) putting carbon taxes on GHG emissions/sinks from land use change, makes expansion of cropland expensive and hence leads to higher land rents and food prices; (3) putting carbon taxes on the energy sector leads to increased demand for biomass for energy use, which also demands land, pushing land rents upwards. Increase in the cost leads to increased food market prices, which in turn lead to reduction in consumption. In addition, in the whole-economy integrated assessment models, the carbon price may also lead to (4) renewable energy implementation, (5) substitution of energy with capital, (6) use of carbon capture and storage technology, and (7) implementation of mitigation abatement technologies to reduce emission intensities. Some models (e.g. AIM, GCAM) apply exogenous marginal abatement cost curves to represent technological reduction in emissions intensity of agricultural production, reducing the degree to which the mitigation policies impact modeled prices and production levels. Carbon prices may also induce a shift to a low-emission industrial structure, which, in AIM, will lead to gross domestic product (GDP) losses and decreased wages and household incomes. Consumers respond to the price increase and income loss by decreasing consumption and shifting to less expensive goods. In most models, carbon tax revenue stays outside of agricultural sectors both on producer and consumer sides and is not properly redistributed to affected people. Mitigation options, carbon price, amount of emission reductions in agriculture and land-use, and emissions coverages were not harmonized across models due to the complexity of the models involved (see for carbon price and the fraction of GHG reduction in Figure S 8). See

Table S 1 for the detailed information of representation of climate change and climate policy in each model.

Our results illustrate how the approach chosen here for implementing emissions mitigation—a global uniform carbon tax on all regions and sectors —can generate negative impacts on low-income regions. On the other hand, outright exclusion of selected regions and/or sectors has been shown to require much larger and often very costly emissions reductions from the balance of the system, and for ambitious mitigation targets (e.g. 2 °C), significant exemptions to the policy may put the mitigation goals out of reach[40, 41, 42, 43, 44].

Baseline (non-climate related) agricultural productivity changes

Baseline (non-climate related) agricultural productivity changes (e.g. from research and extension efforts) were assumed in each model in their own way by changing parameters in line with the SSP storylines and reflecting a wide range of technology developments, such as increasing fertilizer input, improving management or varieties, and expanding irrigation[45]. Figure S 10 reports the resulting yield changes between 2005 and 2050 for selected crops in selected countries that exclude the impacts of climate change. To calculate those impacts on crop yields, the changes in crop yield due to climate change under different climate scenarios (RCPs) are input to the models as a change ratio from the no-climate-change level.

Agricultural economic market

All of the models have in common that they contain agricultural markets with different representations and parameterizations of biophysical and socio-economic processes. Here we focus on the endogenous response to the given changes in the underlying socioeconomic conditions, climate impacts, and mitigation policy. For the demand side, the population and income growth increase food demand, shift the demand curve rightward and raise prices. Responding to the higher price, producers increase their production through expanding crop cultivated area and pasture and increase land productivity (production per unit land area) while consumers decrease their consumption or shift to less expensive goods. Some people might consume insufficient food and face the risk of hunger. Trade globalization helps reallocate supply and demand, decreases food prices and contributes to a lower risk of hunger. In the same way, decreases in crop yields due to climate change shift the supply curve leftward, thus decreasing food supply, raising prices, and resulting in the same responses to the high price.

Agricultural commodity prices are endogenously determined under the supply and demand functions which vary among models due to different functional forms, as well as their parameters such as production cost and demand elasticity, which would not allow for a precise harmonization. For supply side, the models represent dynamic changes in production cost and inputs. Economic growth increases resource-use efficiency and labour productivity, which in turn contributes to decreased crop production cost and price. High pressure on land, which is one of the inputs to agricultural production, eventually leads to high land rent and raises prices. For the demand side, the given population and income growth boost food demand based on income elasticity either implicitly or explicitly represented in each model, shifting the demand curve rightward and thus raising prices. Under a climate policy, the carbon price is placed on emissions from agricultural production and emissions from land-use change, increasing food price. The implementation of land-based mitigation such as bioenergy deployment disincentivizes the use of land for food crop production, thereby increasing land rent and crop prices.

Methods to estimate the population at risk of hunger

To project population at risk of hunger, we adopt an implementation of the FAO's approach[46] in the agricultural economic models previously employed by Hasegawa et al.[5, 47]. The definition of hunger is a state of energy (calorie) deprivation lasting over one year; this does not include the short-lived effects of temporary crises nor does it include inadequate intake of other essential nutrients[48]. The population undernourished is a multiple of the prevalence of the undernourishment (PoU) and the total population. According to the FAO, the PoU is calculated from three key factors: the mean dietary energy availability (kcal/person/day), the mean minimum dietary energy requirement (MDER), and the coefficient of variation (CV) of the domestic distribution of dietary energy consumption in a country. The food distribution within a country is assumed to obey a lognormal distribution which is determined by the mean dietary energy availability (mean) and the equity of the food distribution (variance). The proportion of the population under the MDER is then defined as the PoU. The calorie-based food consumption (kcal/person/day) output from the models was used as the mean dietary energy availability. The future mean MDER is calculated for each year and country using the mean MDER in the base year at the country level[49], adjustment coefficient for the MDER in different age and sex groups[50] and the future population demographics[25] to reflect differences in the MDER across age and sex. The future equality of food distribution was estimated by applying the historical trend of income growth and the improved coefficient of variation (CV) of the food distribution to the future so that the equity is improved along with income growth in future at historical rate up to the present best value (0.2). See Hasegawa et al.[5] for more information.

References

2. Nelson GC, Valin H, Sands RD, Havlík P, Ahammad H, Deryng D*, et al.* Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences* 2014, **111**(9)**:** 3274-3279.

5. Hasegawa T, Fujimori S, Shin Y, Tanaka A, Takahashi K, Masui T. Consequence of Climate Mitigation on the Risk of Hunger. *Environmental Science & Technology* 2015, **49**(12)**:** 7245-7253.

7. UNFCCC. United Nations Framework Convention on Climate Change, 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. 2015.

12. von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, Calvin K*, et al.* Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics* 2014, **45**(1)**:** 3-20.

15. Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E*, et al.* Land-use futures in the shared socio-economic pathways. *Global Environmental Change* 2017, **42:** 331-345.

17. Frank S, Havlík P, Soussana J-F, Levesque A, Valin H, Wollenberg E*, et al.* Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters* 2017, **12**(10)**:** 105004.

21. O'Neill B, Kriegler E, Riahi K, Ebi K, Hallegatte S, Carter T*, et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* 2014, **122**(3)**:** 387-400.

22. van Vuuren D, Stehfest E, Elzen MJ, Kram T, Vliet J, Deetman S*, et al.* RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change* 2011, **109**(1-2)**:** 95-116.

23. Masui T, Matsumoto K, Hijioka Y, Kinoshita T, Nozawa T, Ishiwatari S*, et al.* An emission pathway for stabilization at 6 Wm−2 radiative forcing. *Climatic Change* 2011, **109**(1-2)**:** 59-76.

24. Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S*, et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 2017, **42:** 153-168.

25. IIASA. Shared Socioeconomic Pathways (SSP) Database Version 0.9.3.; 2012.

26. Fujimori S, Su X, Liu J-Y, Hasegawa T, Takahashi K, Masui T*, et al.* Implications of the Paris Agreement in the Context of Long-Term Climate Mitigation Goals. In: Fujimori S, Kainuma M, Masui T (eds). *Post-2020 Climate Action: Global and Asian Perspectives*. Springer Singapore: Singapore, 2017, pp 11-29.

27. Fujimori S, Kubota I, Dai H, Takahashi K, Hasegawa T, Liu J-Y*, et al.* Will international emissions trading help achieve the objectives of the Paris Agreement? *Environmental Research Letters* 2016, **11**(10)**:** 104001.

28. Mosnier A, Havlík P, Valin H, Baker J, Murray B, Feng S*, et al.* Alternative U.S. biofuel mandates and global GHG emissions: The role of land use change, crop management and yield growth. *Energy Policy* 2013, **57:** 602-614.

29. Frank S, Böttcher H, Havlík P, Valin H, Mosnier A, Obersteiner M*, et al.* How effective are the sustainability criteria accompanying the European Union 2020 biofuel targets? *GCB Bioenergy* 2013, **5**(3)**:** 306-314.

30. Zhang YW, McCarl BA. US Agriculture under Climate Change: An Examination of Climate Change Effects on Ease of Achieving RFS2. *Economics Research International* 2013, **2013:** 13.

31. Banse M, van Meijl H, Tabeau A, Woltjer G. Will EU biofuel policies affect global agricultural markets? *European Review of Agricultural Economics* 2008, **35**(2)**:** 117-141.

32. Taylor KE, Stouffer RJ, Meehl GA. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society* 2012, **93**(4)**:** 485-498.

33. Williams JR. The EPIC Model. In: Singh VP (ed). *Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO*, 1995.

34. Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W*, et al.* Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 2007, **13**(3)**:** 679-706.

35. Müller C, Robertson R. Projecting future crop productivity for global economic modeling. *Agric Econ* 2014, **45**(1)**:** 37-50.

36. Elliott J, Kelly D, Chryssanthacopoulos J, Glotter M, Jhunjhnuwala K, Best N*, et al.* The parallel system for integrating impact models and sectors (pSIMS). *Environmental Modelling & Software* 2014, **62**(0)**:** 509-516.

37. Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA*, et al.* The DSSAT cropping system model. *European Journal of Agronomy* 2003, **18**(3-4)**:** 235-265.

38. Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O, Schewe J. The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. *Proceedings of the National Academy of Sciences of the United States of America* 2014, **111**(9)**:** 3228-3232.

39. You L, S.Crespo, Guo Z, Koo J, Ojo W, Sebastian K*, et al.* Spatial Produciton Allocation Model (SPAM) 2000 Version 3 Release 2; 2010.

40. Reisinger A, Havlik P, Riahi K, van Vliet O, Obersteiner M, Herrero M. Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Climatic Change* 2013, **117**(4)**:** 677-690.

41. Gernaat DEHJ, Calvin K, Lucas PL, Luderer G, Otto SAC, Rao S*, et al.* Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change* 2015, **33**(Supplement C)**:** 142-153.

42. Wollenberg E, Richards M, Smith P, Havlík P, Obersteiner M, Tubiello FN*, et al.* Reducing emissions from agriculture to meet the 2 °C target. *Global Change Biology* 2016, **22**(12)**:** 3859-3864.

43. Calvin K, Edmonds J, Bond-Lamberty B, Clarke L, Kim SH, Kyle P*, et al.* 2.6: Limiting climate change to 450 ppm CO2 equivalent in the 21st century. *Energy Economics* 2009, **31**(Supplement 2)**:** S107-S120.

44. Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R*, et al.* Implications of limiting CO2 concentrations for land use and energy. *Science* 2009, **324**(5931)**:** 1183-1186.

45. Robinson S, van Meijl H, Willenbockel D, Valin H, Fujimori S, Masui T*, et al.* Comparing supply-side specifications in models of global agriculture and the food system. *Agricultural Economics* 2014, **45**(1)**:** 21-35.

46. Cafiero C. ADVANCES IN HUNGER MEASUREMENT: TRADITIONAL FAO METHODS AND RECENT INNOVATIONS. Rome: Food and Agriculture Organization of the United Natio; 2014.

47. Hasegawa T, Fujimori S, Takahashi K, Masui T. Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. *Environmental Research Letters* 2015, **10**(1)**:** 014010.

48. FAO I, UNICEF, WFP, WHO. The state of food security and nutrition in the world 2017 Builiding resilience for pease and food security. Rome, Italy: FAO; 2017.

49. FAO. Food security indicators. In: FAO, editor. Rome, Italy; 2013.

50. FAO/WHO. Energy and protein requirements. Geneva, Switzerland: FAO/WHO; 1973.