### 1 Title:

- 2 Risk of increased food insecurity under stringent global climate change mitigation policy
- 3

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- 3839 Introductory paragraph (150 words)
- 40 Food insecurity can be directly exacerbated by climate change due to crop production-related
- 41 impacts of warmer and drier conditions expected in important agricultural regions<sup>1, 2, 3</sup>.
- 42 However, efforts to mitigate climate change through comprehensive, economy-wide
- 43 greenhouse gas emission reductions may also negatively affect food security, due to indirect
- 44 impacts on prices and supplies of key agricultural commodities<sup>4, 5, 6</sup>. Here we conduct a
- 45 multiple model assessment on the combined effects of climate change and climate mitigation
- 46 efforts on agricultural commodity prices, dietary energy availability, and the population at
- 47 risk of hunger. A robust finding is that by 2050, stringent climate mitigation policy, if
- 48 implemented evenly across all sectors and regions, would have a greater negative impact on
- 49 global hunger and food consumption than the direct impacts of climate change. The negative
- 50 impacts would be most prevalent in vulnerable low-income regions such as Sub-Saharan
- 51 Africa and South Asia, where food security problems are already acute.

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54 Main texts (<2000words)

The Paris Agreement, adopted in  $2015^7$ , calls for nations to limit global mean temperature 55 rise well below 2 °C above pre-industrial levels by the end of this century, whilst pursuing 56 57 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 58 59 consumption and agricultural activities. For example, carbon taxes have been introduced in 60 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 61 policies in the form of tax exemptions or subsidies, or biofuel blending mandates<sup>8</sup>, leading to 62 63 the conversion of substantial amounts of crops into fuel. The ambitious GHG emissions 64 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 65 66 bioenergy plantation expansion and afforestation. This would compete with land and 67 freshwater requirements for food production, with a consequent risk of increasing food insecurity<sup>4, 5, 6</sup>. Moreover, since agricultural production is a primary source of income for 68 many people in developing regions, climate change mitigation targeting emissions-intensive 69 agricultural activities could also exacerbate rural poverty<sup>9, 10</sup>. 70 71

Many studies have quantified the direct impacts of climate change on agricultural 72 production<sup>1</sup>, markets<sup>2, 11, 12</sup> and food security<sup>3, 13, 14</sup>. For example, a recent global agricultural 73 economic model comparison study<sup>2</sup> found that future climate change lowers major crop 74 yields by 17%, increases market prices by 20% and reduces related consumption by 3% by 75 76 2050, after adaptation of production across regions. Another integrated assessment of the 77 impacts of emissions mitigation policies on the agricultural sector consistent with a 2 °C goal<sup>15</sup> shows that land-based mitigation efforts would increase food prices on average by 78 79 110% in 2100.

80

Here we present a model ensemble assessment of the combined effects of climate change 81 82 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 83 dimensions: (1) selected "shared socio-economic pathways" (SSPs): "sustainability" (SSP1), 84 "middle-of-the-road" (SSP2), and "regional-rivalry" (SSP3); (2) climate change impacts on 85 crop yields corresponding to 2°C and 2.7°C increase by 2100 from the pre-industrial level 86 87 (RCP2.6 and RCP6.0); and (3) climate change mitigation efforts: ambitious climate 88 mitigation policies of a 2°C scenario (reducing emissions down to RCP2.6 emission levels) 89 versus no climate action<sup>6</sup>. We also present a baseline scenario that assumes the current 90 climatic conditions would prevail in the future (see Methods and Table S 1 for scenario 91 architecture).

92

93 The selected scenarios allow us to verify the robustness of our results across a wide range of 94 potential future socio-economic developments, to separate the pure effects of climate impacts 95 and of ambitious mitigation efforts, and to keep consistency between severity of climate 96 impacts and emissions mitigation levels in the different agricultural modelling frameworks. 97 All of the models implemented emissions mitigation using a global uniform carbon tax on 98 GHG emissions from different sectors (i.e., agriculture, land-use and/or non-agricultural sectors), the most standard approach in the literature<sup>4, 5, 15, 16</sup>. This uniform approach allows 99 100 models to identify the most cost-efficient emissions pathway for a given climate target, and 101 ensures the comparability of the results across modelling frameworks. Each model then shows specific endogenous responses, which include adjustments to production systems, 102 103 technologies, and food demand and trade, among others. In all models, carbon prices lead to

- 104 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 105
- production costs depending on the GHG intensity of the production<sup>17</sup>; (2) the carbon tax on 106
- 107 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 108
- induces an increase in the biofuel demand from the energy system, which further increases 109
- the demands for land and hence again pushes the land rents upwards. The resulting increase 110
- in food commodity prices decreases food consumption or shifts demand to less expensive 111
- 112 food products, with implications for the prevalence of hunger.
- 113
- 114 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 115
- 116 policies or current biofuel mandates is technically possible for the models, we do not
- 117 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 118
- this study, and selected one global climate and crop model combination for each RCP and 119
- 120 each assumption on CO<sub>2</sub> fertilization that is closest to the median at global aggregation<sup>6</sup>. CO<sub>2</sub>
- effects still has disputed impacts on food production as it increases biomass yields but 121
- decreases nutrient content. We assume similar to prior work<sup>2</sup> no  $CO_2$  fertilization effect in the 122
- 123 main scenarios (See Methods) but discuss the influence of varying this assumption for our results in Supplementary discussion S9.
- 124 125

Our analysis shows that by 2050, the potential for a sizeable increase in the risk of hunger is 126 higher in the RCP2.6 scenarios under climate mitigation than in the RCP6.0 scenarios without 127 mitigation in all socio-economic futures and economic models, despite the fact that RCP6.0 128 129 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, 130 the population at risk of hunger in 2050 increases by 24 million (2-56 million) with the 131 132 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 133 emissions mitigation policies of the RCP2.6 scenario (Figure 1a and Figure S 14 for the 134 global and regional baseline scenario). Most of the increase in hunger in the RCP2.6 135 scenarios is caused by the implementation of climate mitigation policies, not the climate 136 137 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 138 139 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 140 141 scenarios). These results imply that inclusive carbon taxation aimed at ambitious climate 142 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 143 without these policies. Although changes in international commodity trade flows can help 144 145 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 146

using the full range of the climate and crop models selected, with and without CO<sub>2</sub> 147

- 148 fertilization effects, leads to similar observations (Supplementary discussion S8 and S9 with
- 149 Figure S5 and S6 for the range of model selection and for CO<sub>2</sub> fertilization assumptions, respectively).
- 150
- 151
- Figure 2 presents a more detailed analysis of food security implications using several 152
- different indicators. Mean dietary energy availability indicates food availability at an 153

aggregated regional level while food prices, per-capita food expenditure, and the population 154

- at risk of hunger indicate food access<sup>18</sup>. Most models agree that mitigation policies linearly 155
- increase food prices and expenditure, decrease food availability, and increase the risk of 156
- hunger. Mitigation policies contribute to more than half of the overall price increases of crops 157
- and livestock products (Figure S 12). Particularly, the prices of the livestock products 158
- increase due to their comparatively higher GHG emission intensity and the higher prices of 159
- feed products and land rents both for pasture land and crop land. Price impacts and 160
- consequent consumption declines tend to be stronger for livestock products than for staple 161 crops (Figure S 12, Figure S 13).
- 162
- 163

Regional estimates also deserve specific attention, considering the regional heterogeneity in 164 climate change impacts and vulnerability. In Sub-Saharan Africa and South Asia (India and 165 166 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 167 12 and 16 million people in 2050, respectively, on average, across all models in the RCP2.6 168 and SSP2 scenario (Figure 3a). These two regions account for 40% and 20%, respectively, of 169 the global population at risk of hunger under climate mitigation in 2050. Moreover, most 170 models show a great degree of price sensitivity of food demands in low-income regions, as 171

- 172 compared with high-income ones (Figure 3b).
- 173

Our findings should not be interpreted to downplay the importance of future GHG emissions 174 175 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 176 policies in upcoming decades, e.g. targeted schemes encouraging more productive and 177 178 resilient agricultural production systems and the importance of incorporating complementary

- 179 policies (e.g. safety-net programs) that compensate or counter-act the impacts of the climate
- change mitigation policies on vulnerable regions. 180
- 181

182 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 183

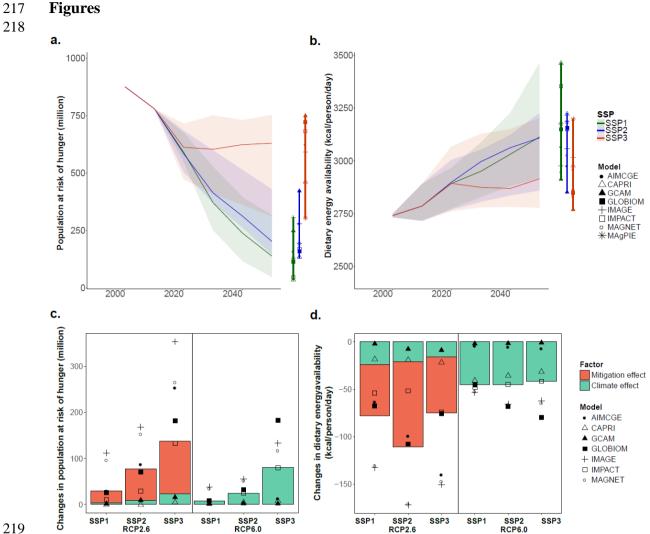
health<sup>19</sup>. Revenue from carbon taxes would bring a new source of income which could be 184 used for food aid programs in low-income nations. Moreover, production systems in food 185

- insecure regions are often less GHG emissions and resource efficient than those in developed 186
- countries. For example, the developing world contributes 75% of global GHG emissions from 187
- ruminants while it supplies only half of milk and beef<sup>20</sup>. Thus, the transfer of resource-188
- 189 efficient production technologies, including land- and emissions-saving ones, to developing
- 190 regions could both contribute to climate mitigation and economic development<sup>4</sup>. Combining
- 191 climate policies with these other measures could promote food security and simultaneously 192 reduce poverty and improve health conditions, increasing resilience of the food production
- 193 systems to climate change and contributing to environmental sustainability.
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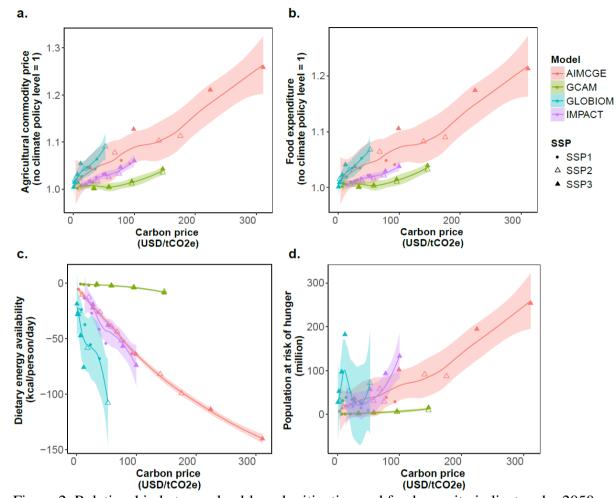
195 Food security is a multi-dimensional and -disciplinary challenge, spanning scales from the global to local levels. In this study, we have focused on analyzing the potential consequences 196 of climate change and emissions mitigation policies on two components of food security 197 198 (food availability and food access) across an intersection of alternative futures in the socio-

- 199 economic (SSPs), climate (RCPs), and mitigation policy spaces. We used a model ensemble
- 200 to better assess the uncertainty inherent to the research questions addressed. Our analysis
- 201 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 202
- 203 dynamic socio-economic conditions.

While climate change is a global phenomenon, its specific impacts and efforts to mitigate its 205 impacts will be realized at national and local levels. As such, future research will be required 206 207 to assess the unique local and national challenges to adapting to and mitigating climate 208 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 209 diversity, and their role in human health. Despite the need for further research, we believe 210 211 this study helps improve understanding of the potential interactions between varied policy objectives within alternative climate, economic, and policy futures. In particular, it highlights 212 the need for carefully designed mitigation policies for agriculture and land use, to ensure that 213 214 progress towards climate stabilization and food security can be simultaneously achieved. 215



220 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 221 baseline scenario under different socio-economic scenarios (SSPs). Ribbons and error bars 222 223 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 224 mitigation scenarios (RCPs) in 2050. Bars shows median level of individual effect across 225 226 models. Symbols show the combined effects for each model. MAgPIE is excluded due to inelastic food demand. 227



229 230 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 231

- for three SSPs. The range shows the 95% confidence level interval. This figure includes the 232 233 model where carbon price is available.

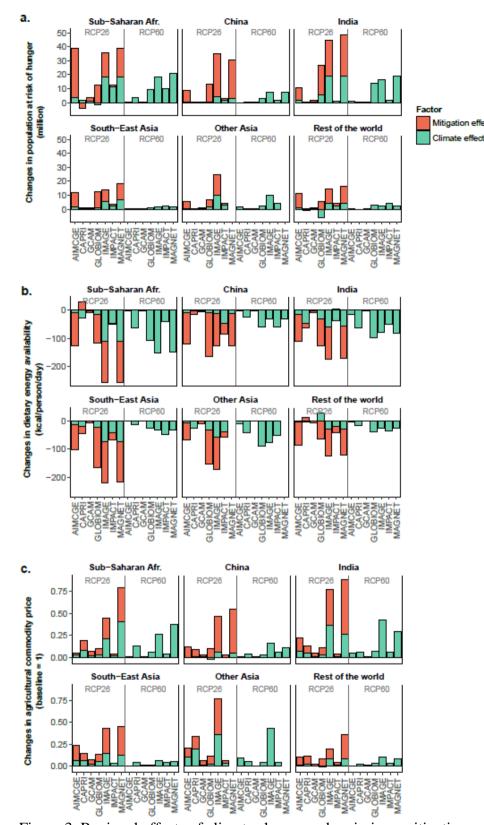


Figure 3 Regional effects of climate change and emissions mitigation on a) population at risk of hunger, b) mean dietary energy availability and c) agricultural commodity price in 2050 under intermediate socio-economic scenario (SSP2). Values indicate changes from the baseline scenario with no climate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

to inelastic food demand. The value of India includes that of Other Asia in MAGNET.

240	References		
241 242 243 244	1.	Asseng S, Ewert F, Martre P, Rötter RP, Lobell DB, Cammarano D, <i>et al.</i> Rising temperatures reduce global wheat production. <i>Nature Climate Change</i> 2015, <b>5:</b> 5.	
245 246 247 248	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. <i>Proceedings of the National Academy of Sciences</i> 2014, <b>111</b> (9): 3274-3279.	
249 250 251	3.	Rosenzweig C, Parry ML. Potential impact of climate change on world food supply. <i>Nature</i> 1994, <b>367</b> (6459): 6.	
252 253 254 255	4.	Havlík P, Valin H, Herrero M, Obersteiner M, Schmid E, Rufino MC, et al. Climate change mitigation through livestock system transitions. <i>Proceedings of the National Academy of Sciences</i> 2014.	
256 257 258 259	5.	Hasegawa T, Fujimori S, Shin Y, Tanaka A, Takahashi K, Masui T. Consequence of Climate Mitigation on the Risk of Hunger. <i>Environmental Science &amp; Technology</i> 2015, <b>49</b> (12): 7245- 7253.	
260 261 262 263	6.	Meijl Hv, Havlik P, Lotze-Campen H, Stehfest E, Witzke P, Domínguez IP, <i>et al</i> . Comparing impacts of climate change and mitigation on global agriculture by 2050. <i>Environmental Research Letters</i> 2018, <b>13</b> (6): 064021.	
264 265 266 267	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.	
268 269 270 271	8.	REN21. Renewables 2007 Global Status Report (Paris: REN21 Secretariat and Washington, DC:Worldwatch Institute. : Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.; 2008.	
271 272 273 274	9.	Zekarias H, Thomas H, Alla G. Climate change mitigation policies and poverty in developing countries. <i>Environmental Research Letters</i> 2013, <b>8</b> (3): 035009.	
275 276 277	10.	Hertel TW, Rosch SD. Climate Change, Agriculture, and Poverty. <i>Applied Economic Perspectives and Policy</i> 2010, <b>32</b> (3): 355-385.	
278 279 280 281	11.	Lotze-Campen H, von Lampe M, Kyle P, Fujimori S, Havlik P, van Meijl H, <i>et al.</i> Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. <i>Agricultural Economics</i> 2014, <b>45</b> (1): 103-116.	
282 283 284 285	12.	von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, Calvin K, <i>et al.</i> Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. <i>Agricultural Economics</i> 2014, <b>45</b> (1): 3-20.	
286 287 288 289	13.	Baldos ULC, Hertel TW. Global food security in 2050: the role of agricultural productivity and climate change. <i>Australian Journal of Agricultural and Resource Economics</i> 2014, <b>58</b> (4): 554-570.	

290 14. Hasegawa T, Fujimori S, Shin Y, Takahashi K, Masui T, Tanaka A. Climate Change Impact and 291 Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. 292 Environmental Science & Technology 2014, 48(1): 438-445. 293 294 15. Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, et al. Land-use futures in 295 the shared socio-economic pathways. Global Environmental Change 2017, 42: 331-345. 296 297 16. Popp A, Rose SK, Calvin K, Van Vuuren DP, Dietrich JP, Wise M, et al. Land-use transition for 298 bioenergy and climate stabilization: model comparison of drivers, impacts and interactions 299 with other land use based mitigation options. Climatic Change 2014, 123(3): 495-509. 300 301 17. Frank S, Havlík P, Soussana J-F, Levesque A, Valin H, Wollenberg E, et al. Reducing 302 greenhouse gas emissions in agriculture without compromising food security? 303 Environmental Research Letters 2017, 12(10): 105004. 304 305 18. FAO. Food security indicators. In: FAO, editor. Rome, Italy; 2016. 306 307 19. Springmann M, Mason-D/'Croz D, Robinson S, Wiebe K, Godfray HCJ, Rayner M, et al. 308 Mitigation potential and global health impacts from emissions pricing of food commodities. 309 Nature Clim Change 2017, 7(1): 69-74. 310 311 20. Herrero M, Havlík P, Valin H, Notenbaert A, Rufino MC, Thornton PK, et al. Biomass use, 312 production, feed efficiencies, and greenhouse gas emissions from global livestock systems. 313 Proceedings of the National Academy of Sciences 2013, 110(52): 20888-20893. 314 315

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- 330

# 331 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),
- 338 B.L.B. and H.L.C. (MAgPIE); all authors provided feedback and contributed to writing the paper.
- 339 340

# 341 **Competing interests**

- 342 The authors have declared that no competing interests exist.
- 343

344 The views expressed are purely those of the authors and may not in any circumstances be regarded as 345 stating an official position of the European Commission or the other institutions involved.

346

# 347 Data availability

- 348 Scenario data for all the scenarios will be made accessible online via the repository:
- 349 http://data.europa.eu/89h/b6722b2e-483b-4f2e-ab45-4eb518939134.
- 350

# 351 Methods

- 352 We used eight agricultural economic models or integrated assessment models (IAMs) which
- 353 sufficiently represent agricultural market and land use to assess the interaction between food
- 354 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.
- 358

# 359 Scenario settings

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

The SSPs are representative future scenarios, including both qualitative and quantitative 368 information in terms of challenges in mitigation and adaptation to climate change. For 369 climate change and climate policy dimensions, we utilize four cases: a baseline scenario with 370 no climate changes (NoCC), a climate change scenario where the climate impacts from 371 RCP6.0 was implemented, and climate mitigation scenarios without and with residual climate 372 change impacts. The comparison between baseline and climate change scenarios allows to 373 374 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 375 376 climate policy ("Mitigation effect" of RCP2.6). Comparing scenarios with and without the 377 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 378 condition, we harmonized the exogenous climate impacts on agricultural productivity by 379 380 using crop yield data under two Representative Concentration Pathways (RCPs) [the 381 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 382 with the Paris Agreement<sup>7</sup> to achieve more than 66% chance to stay below 2.0°C]. RCP2.6 383 384 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<sup>22, 23</sup>. RCP2.6 corresponds 385 roughly to a global mean temperature rise from preindustrial times to less than 2°C by 2100 386 while RCP6.0 has a 2.7°C rise. In the SSP scenarios<sup>24</sup>, most models' reference scenarios had 387 forcing levels in 2100 of around 7  $W/m^2$ . Thus, while no-mitigation scenarios are generally 388 389 between RCP6.0 and RCP8.5, here we have selected RCP6.0 because it is relatively closer to 390  $7 \text{ W/m}^2$ .

391

#### 392 Socioeconomic assumptions and data.

393 Each model changes socio-economic assumptions such as population, gross domestic product (GDP), dietary preferences, agricultural intensification irrespective of climate change, land-394 use regulation and international trade according to the SSP storylines<sup>15</sup>. All models were run 395 with exogenous GDP and population, which were harmonized across models using the SSP 396 socio-economic data<sup>25</sup>. In SSP2, the global population reaches 9.3 billion by 2050, an 397 increase of 35% relative to 2010, and global GDP triples. For other characteristics captured 398 by SSPs, the modeling teams made their own assumptions on how to best represent the 399 described future trends. It is expected that model results for the same scenario will differ 400 401 significantly, due to different interpretations and implementations of the SSP storylines across models. The effectiveness of agricultural technologies (e.g., improved crops, irrigation 402 403 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 404 405 assume present-day agricultural policies to remain in place through calibration (e.g., price wedges based on statistical data<sup>12</sup>). Although all of the current national agricultural policies 406 and governmental actions were implicitly covered, some of the specific features of these 407 policies, going beyond the relative price difference were not captured. There are some studies 408 409 considering the current short-term climate targets (e.g. the Nationally determined contributions (NDCs))<sup>26, 27</sup> or the biofuel policies or mandates (e.g. the U.S. renewable fuel 410 standard (RFS2) or European Union renewable energy targets in the Renewable Energy 411 Directive (RED)<sup>28, 29, 30, 31</sup>. Although the implementation of these policies is technically 412 possible for the models used in this study, here we focus on the implications of climate 413 414 change and emissions mitigation for food security and do not explicitly consider these 415 policies. More detailed descriptions of the individual models can be found in each model paper shown in Table S 2. 416

#### 418 Climate change effects on crop yield

In the scenarios with climate change, we used results of the yield change of up to twelve 419 types of crops (maize, millet, rice, wheat, rapeseed, soybeans, sunflower, other oilseeds, 420 cassava, ground nuts, sugar beet and sugar cane) estimated by using the five global earth 421 system or climate models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-422 ESM2M and NorESM1-M) contributing to the fifth phase of the Coupled Model 423 Intercomparison Project (CMIP5)<sup>32</sup>, and three global crop models (EPIC<sup>33</sup>, LPJmL<sup>34, 35</sup>, 424 pDSSAT<sup>36, 37</sup>) that contributed to the ISI-MIP fast-track data archive<sup>38</sup>. These three crop 425 426 models were selected according to data availability of at least four major crop types (rice, 427 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 428 used in the economic models, we apply the same methods as prior AgMIP research<sup>2</sup> (Table 429 430 S5). For crops where yield impact data are not available, we used the average yield impacts 431 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 432 values using the present crop- and irrigation system specific areas based on the Spatial 433 Production Allocation Model (SPAM) data base<sup>39</sup>. Direct climate change impacts on 434 livestock and fish production are not considered due to data limitation. Since the portion of 435 the global population that is most vulnerable to food security issues tend to rely mostly on 436 437 crops for food, this assumption would likely not affect change our findings, but further analysis would be required for confirmation. 438

439

#### 440 Model representation of climate policy

All models implemented a global uniform carbon price on greenhouse gas emissions across 441 442 sectors in order to represent ambitious mitigation measures. The uniform carbon price 443 ensures cost-effective achievement of emission reduction, but does not necessarily minimize 444 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 445 446 emissions directly increases the costs of production proportional to the GHG intensity of the production<sup>17</sup>, and therefore food prices; (2) putting carbon taxes on GHG emissions/sinks 447 from land use change, makes expansion of cropland expensive and hence leads to higher land 448 449 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 450 the cost leads to increased food market prices, which in turn lead to reduction in 451 452 consumption. In addition, in the whole-economy integrated assessment models, the carbon 453 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 454 mitigation abatement technologies to reduce emission intensities. Some models (e.g. AIM, 455 GCAM) apply exogenous marginal abatement cost curves to represent technological 456 reduction in emissions intensity of agricultural production, reducing the degree to which the 457 mitigation policies impact modeled prices and production levels. Carbon prices may also 458 459 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 460 respond to the price increase and income loss by decreasing consumption and shifting to less 461 expensive goods. In most models, carbon tax revenue stays outside of agricultural sectors 462 both on producer and consumer sides and is not properly redistributed to affected people. 463 Mitigation options, carbon price, amount of emission reductions in agriculture and land-use, 464 and emissions coverages were not harmonized across models due to the complexity of the 465 models involved (see for carbon price and the fraction of GHG reduction in Figure S 8). See 466

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

469

470 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

472 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<sup>40, 41, 42, 43, 44</sup>.
- 476 477

# 478 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

481 line with the SSP storylines and reflecting a wide range of technology developments, such as

482 increasing fertilizer input, improving management or varieties, and expanding irrigation<sup>45</sup>.

483 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
- 484 selected countries that exclude the impacts of eminate change. To calculate those impacts of 485 crop yields, the changes in crop yield due to climate change under different climate scenarios
- 486 (RCPs) are input to the models as a change ratio from the no-climate-change level.
- 487

# 488 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

- 491 focus on the endogenous response to the given changes in the underlying socioeconomic
- 492 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
- 494 Responding to the inglief price, producers increase their production through expanding cr 495 cultivated area and pasture and increase land productivity (production per unit land area)
- 496 while consumers decrease their consumption or shift to less expensive goods. Some people

497 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 supplycurve leftward, thus decreasing food supply, raising prices, and resulting in the same
- 501 responses to the high price.
- 502

Agricultural commodity prices are endogenously determined under the supply and demand 503 504 functions which vary among models due to different functional forms, as well as their 505 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 506 cost and inputs. Economic growth increases resource-use efficiency and labour productivity, 507 508 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 509 raises prices. For the demand side, the given population and income growth boost food 510 511 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 512 513 carbon price is placed on emissions from agricultural production and emissions from land-use 514 change, increasing food price. The implementation of land-based mitigation such as bioenergy deployment disincentivizes the use of land for food crop production, thereby 515

516 increasing land rent and crop prices.

### 518 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<sup>46</sup> 519 in the agricultural economic models previously employed by Hasegawa et al.<sup>5, 47</sup>. The 520 definition of hunger is a state of energy (calorie) deprivation lasting over one year; this does 521 not include the short-lived effects of temporary crises nor does it include inadequate intake of 522 other essential nutrients<sup>48</sup>. The population undernourished is a multiple of the prevalence of 523 the undernourishment (PoU) and the total population. According to the FAO, the PoU is 524 525 calculated from three key factors: the mean dietary energy availability (kcal/person/day), the 526 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 527 within a country is assumed to obey a lognormal distribution which is determined by the 528 529 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-530 based food consumption (kcal/person/day) output from the models was used as the mean 531 dietary energy availability. The future mean MDER is calculated for each year and country 532 using the mean MDER in the base year at the country level<sup>49</sup>, adjustment coefficient for the 533 MDER in different age and sex groups<sup>50</sup> and the future population demographics<sup>25</sup> to reflect 534 differences in the MDER across age and sex. The future equality of food distribution was 535 536 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 537 538 income growth in future at historical rate up to the present best value (0.2). See Hasegawa et

539 al.<sup>5</sup> for more information.

542 543	References		
544	2.	Nelson GC, Valin H, Sands RD, Havlík P, Ahammad H, Deryng D, et al. Climate change effects	
545		on agriculture: Economic responses to biophysical shocks. Proceedings of the National	
546		Academy of Sciences 2014, <b>111</b> (9): 3274-3279.	
547		//ddc/// 0/ 00/c//cc2 201 // ==(0// 02/01	
548	5.	Hasegawa T, Fujimori S, Shin Y, Tanaka A, Takahashi K, Masui T. Consequence of Climate	
549	5.	Mitigation on the Risk of Hunger. Environmental Science & Technology 2015, <b>49</b> (12): 7245-	
550		7253.	
550		7255.	
552	7.	UNFCCC. United Nations Framework Convention on Climate Change, Adoption of the Paris	
552 553	7.	Agreement. Proposal by the President (1/CP21) [cited 2016 02, Feb.] Available from:	
555 554			
555 555		http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf. 2015.	
	10	ven Lemme M. Willenheelvel D. Aberemed H. Diene F. Cei V. Celvin K. et al. Why de clebel	
556	12.	von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, Calvin K, et al. Why do global	
557		long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model	
558		Intercomparison. Agricultural Economics 2014, 45(1): 3-20.	
559			
560	15.	Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, et al. Land-use futures in	
561		the shared socio-economic pathways. Global Environmental Change 2017, 42: 331-345.	
562	47		
563	17.	Frank S, Havlík P, Soussana J-F, Levesque A, Valin H, Wollenberg E, et al. Reducing	
564		greenhouse gas emissions in agriculture without compromising food security?	
565		Environmental Research Letters 2017, <b>12</b> (10): 105004.	
566			
567	21.	O'Neill B, Kriegler E, Riahi K, Ebi K, Hallegatte S, Carter T, et al. A new scenario framework for	
568		climate change research: the concept of shared socioeconomic pathways. <i>Climatic Change</i>	
569		2014, <b>122</b> (3): 387-400.	
570			
571	22.	van Vuuren D, Stehfest E, Elzen MJ, Kram T, Vliet J, Deetman S, et al. RCP2.6: exploring the	
572		possibility to keep global mean temperature increase below 2°C. <i>Climatic Change</i> 2011,	
573		<b>109</b> (1-2): 95-116.	
574			
575	23.	Masui T, Matsumoto K, Hijioka Y, Kinoshita T, Nozawa T, Ishiwatari S, et al. An emission	
576		pathway for stabilization at 6 Wm-2 radiative forcing. <i>Climatic Change</i> 2011, <b>109</b> (1-2): 59-	
577		76.	
578			
579	24.	Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, et al. The Shared	
580		Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions	
581		implications: An overview. Global Environmental Change 2017, 42: 153-168.	
582			
583	25.	IIASA. Shared Socioeconomic Pathways (SSP) Database Version 0.9.3.; 2012.	
584			
585	26.	Fujimori S, Su X, Liu J-Y, Hasegawa T, Takahashi K, Masui T, et al. Implications of the Paris	
586		Agreement in the Context of Long-Term Climate Mitigation Goals. In: Fujimori S, Kainuma M,	
587		Masui T (eds). Post-2020 Climate Action: Global and Asian Perspectives. Springer Singapore:	
588		Singapore, 2017, pp 11-29.	
589			
590	27.	Fujimori S, Kubota I, Dai H, Takahashi K, Hasegawa T, Liu J-Y <i>, et al.</i> Will international	
591		emissions trading help achieve the objectives of the Paris Agreement? Environmental	
592		Research Letters 2016, <b>11</b> (10): 104001.	
593			

594 28. Mosnier A, Havlík P, Valin H, Baker J, Murray B, Feng S, et al. Alternative U.S. biofuel 595 mandates and global GHG emissions: The role of land use change, crop management and 596 yield growth. Energy Policy 2013, 57: 602-614. 597 598 29. Frank S, Böttcher H, Havlík P, Valin H, Mosnier A, Obersteiner M, et al. How effective are the 599 sustainability criteria accompanying the European Union 2020 biofuel targets? GCB 600 Bioenergy 2013, 5(3): 306-314. 601 602 30. Zhang YW, McCarl BA. US Agriculture under Climate Change: An Examination of Climate 603 Change Effects on Ease of Achieving RFS2. Economics Research International 2013, 2013: 13. 604 605 Banse M, van Meijl H, Tabeau A, Woltjer G. Will EU biofuel policies affect global agricultural 31. 606 markets? European Review of Agricultural Economics 2008, 35(2): 117-141. 607 608 32. Taylor KE, Stouffer RJ, Meehl GA. An Overview of CMIP5 and the Experiment Design. Bulletin 609 of the American Meteorological Society 2012, 93(4): 485-498. 610 611 33. Williams JR. The EPIC Model. In: Singh VP (ed). Computer Models of Watershed Hydrology, 612 Water Resources Publications, Highlands Ranch, CO, 1995. 613 614 34. Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, et al. Modelling the role of 615 agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 616 2007, 13(3): 679-706. 617 618 35. Müller C, Robertson R. Projecting future crop productivity for global economic modeling. 619 Agric Econ 2014, 45(1): 37-50. 620 621 36. Elliott J, Kelly D, Chryssanthacopoulos J, Glotter M, Jhunjhnuwala K, Best N, et al. The parallel 622 system for integrating impact models and sectors (pSIMS). Environmental Modelling & 623 Software 2014, 62(0): 509-516. 624 625 37. Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, et al. The DSSAT 626 cropping system model. European Journal of Agronomy 2003, 18(3-4): 235-265. 627 628 38. Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O, Schewe J. The Inter-Sectoral Impact 629 Model Intercomparison Project (ISI-MIP): Project framework. Proceedings of the National 630 Academy of Sciences of the United States of America 2014, **111**(9): 3228-3232. 631 632 39. You L, S.Crespo, Guo Z, Koo J, Ojo W, Sebastian K, et al. Spatial Produciton Allocation Model 633 (SPAM) 2000 Version 3 Release 2; 2010. 634 635 40. Reisinger A, Havlik P, Riahi K, van Vliet O, Obersteiner M, Herrero M. Implications of 636 alternative metrics for global mitigation costs and greenhouse gas emissions from 637 agriculture. *Climatic Change* 2013, **117**(4): 677-690. 638 639 41. Gernaat DEHJ, Calvin K, Lucas PL, Luderer G, Otto SAC, Rao S, et al. Understanding the 640 contribution of non-carbon dioxide gases in deep mitigation scenarios. Global Environmental 641 Change 2015, 33(Supplement C): 142-153. 642

643 42. Wollenberg E, Richards M, Smith P, Havlík P, Obersteiner M, Tubiello FN, et al. Reducing 644 emissions from agriculture to meet the 2 °C target. Global Change Biology 2016, 22(12): 3859-3864. 645 646 647 43. Calvin K, Edmonds J, Bond-Lamberty B, Clarke L, Kim SH, Kyle P, et al. 2.6: Limiting climate 648 change to 450 ppm CO2 equivalent in the 21st century. Energy Economics 2009, 649 31(Supplement 2): S107-S120. 650 651 44. Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, et al. Implications of 652 limiting CO2 concentrations for land use and energy. Science 2009, 324(5931): 1183-1186. 653 654 45. Robinson S, van Meijl H, Willenbockel D, Valin H, Fujimori S, Masui T, et al. Comparing 655 supply-side specifications in models of global agriculture and the food system. Agricultural 656 Economics 2014, 45(1): 21-35. 657 658 Cafiero C. ADVANCES IN HUNGER MEASUREMENT: TRADITIONAL FAO METHODS AND 46. 659 RECENT INNOVATIONS. Rome: Food and Agriculture Organization of the United Natio; 2014. 660 47. Hasegawa T, Fujimori S, Takahashi K, Masui T. Scenarios for the risk of hunger in the twenty-661 662 first century using Shared Socioeconomic Pathways. Environmental Research Letters 2015, 663 **10**(1): 014010. 664 665 48. FAO I, UNICEF, WFP, WHO. The state of food security and nutrition in the world 2017 666 Builiding resilience for pease and food security. Rome, Italy: FAO; 2017. 667 668 49. FAO. Food security indicators. In: FAO, editor. Rome, Italy; 2013. 669 670 50. FAO/WHO. Energy and protein requirements. Geneva, Switzerland: FAO/WHO; 1973. 671 672