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1 **Title:**

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

3
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38
39 *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^{1, 2, 3}.

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^{4, 5, 6}. 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.

54 Main texts (<2000words)

55 The Paris Agreement, adopted in 2015⁷, calls for nations to limit global mean temperature
56 rise well below 2 °C above pre-industrial levels by the end of this century, whilst pursuing
57 efforts to limit warming to 1.5 °C. In the last decade, climate related policies have been
58 implemented and have influenced not only greenhouse gas (GHG) emissions but also energy
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
61 producers such as the United States, Brazil, and EU countries have initiated ambitious biofuel
62 policies in the form of tax exemptions or subsidies, or biofuel blending mandates⁸, leading to
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
65 climate change on agriculture and food production, but may also lead to much larger scale
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
68 insecurity^{4, 5, 6}. Moreover, since agricultural production is a primary source of income for
69 many people in developing regions, climate change mitigation targeting emissions-intensive
70 agricultural activities could also exacerbate rural poverty^{9, 10}.

71
72 Many studies have quantified the direct impacts of climate change on agricultural
73 production¹, markets^{2, 11, 12} and food security^{3, 13, 14}. For example, a recent global agricultural
74 economic model comparison study² found that future climate change lowers major crop
75 yields by 17%, increases market prices by 20% and reduces related consumption by 3% by
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
78 goal¹⁵ shows that land-based mitigation efforts would increase food prices on average by
79 110% in 2100.

80
81 Here we present a model ensemble assessment of the combined effects of climate change
82 impacts and emissions mitigation efforts on food security and hunger. We compare the results
83 of eight global agricultural economic models (Table S 2) on a set of scenarios covering three
84 dimensions: (1) selected “shared socio-economic pathways” (SSPs): “sustainability” (SSP1),
85 “middle-of-the-road” (SSP2), and “regional-rivalry” (SSP3); (2) climate change impacts on
86 crop yields corresponding to 2°C and 2.7°C increase by 2100 from the pre-industrial level
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 action⁶. 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
99 sectors), the most standard approach in the literature^{4, 5, 15, 16}. This uniform approach allows
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
102 shows specific endogenous responses, which include adjustments to production systems,
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
105 simultaneously: (1) the carbon tax on agricultural GHG emissions directly increases the
106 production costs depending on the GHG intensity of the production¹⁷; (2) the carbon tax on
107 the carbon emissions/sequestration associated with land-use change makes expansion of
108 agricultural land more expensive and hence leads to higher land rents; (3) the carbon tax
109 induces an increase in the biofuel demand from the energy system, which further increases
110 the demands for land and hence again pushes the land rents upwards. The resulting increase
111 in food commodity prices decreases food consumption or shifts demand to less expensive
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
115 measures in the long run are considered. Although the implementation of short-term climate
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
118 results from five global climate models and three global crop models that were suitable for
119 this study, and selected one global climate and crop model combination for each RCP and
120 each assumption on CO₂ fertilization that is closest to the median at global aggregation⁶. CO₂
121 effects still has disputed impacts on food production as it increases biomass yields but
122 decreases nutrient content. We assume similar to prior work² no CO₂ fertilization effect in the
123 main scenarios (See Methods) but discuss the influence of varying this assumption for our
124 results in Supplementary discussion S9.

125
126 Our analysis shows that by 2050, the potential for a sizeable increase in the risk of hunger is
127 higher in the RCP2.6 scenarios under climate mitigation than in the RCP6.0 scenarios without
128 mitigation in all socio-economic futures and economic models, despite the fact that RCP6.0
129 scenarios have more severe climate change and greater reductions in crop yields (Figure 1-c;
130 Figure3a for regional information; Figure S 11). With the SSP2 socio-economic backdrop,
131 the population at risk of hunger in 2050 increases by 24 million (2-56 million) with the
132 climate impacts of the RCP6.0 scenario, compared with the baseline scenario. This number
133 increases by around 78 million (0-170 million) people with the combined climate impacts and
134 emissions mitigation policies of the RCP2.6 scenario (Figure 1a and Figure S 14 for the
135 global and regional baseline scenario). Most of the increase in hunger in the RCP2.6
136 scenarios is caused by the implementation of climate mitigation policies, not the climate
137 change impacts. Also for SSP2, average global caloric availability is lower by 45
138 kcal/person/day (2-68 kcal/person/day) under the RCP6.0 scenario compared to the baseline
139 scenario, while the level is lower by 110 kcal/person/day (8-170 kcal/person/day) under the
140 RCP2.6 scenario compared to the baseline scenario (Figure 1d; Figure 1b for baseline
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
143 prices, decrease food consumption, and put more people at risk of hunger than in a future
144 without these policies. Although changes in international commodity trade flows can help
145 reallocate food from surplus to deficit countries, dampening the increases in food prices and
146 risk of hunger, the adverse effects of mitigation efforts still remain. Our sensitivity analyses
147 using the full range of the climate and crop models selected, with and without CO₂
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 CO₂ fertilization assumptions,
150 respectively).

151
152 Figure 2 presents a more detailed analysis of food security implications using several
153 different indicators. Mean dietary energy availability indicates food availability at an

154 aggregated regional level while food prices, per-capita food expenditure, and the population
155 at risk of hunger indicate food access¹⁸. Most models agree that mitigation policies linearly
156 increase food prices and expenditure, decrease food availability, and increase the risk of
157 hunger. Mitigation policies contribute to more than half of the overall price increases of crops
158 and livestock products (Figure S 12). Particularly, the prices of the livestock products
159 increase due to their comparatively higher GHG emission intensity and the higher prices of
160 feed products and land rents both for pasture land and crop land. Price impacts and
161 consequent consumption declines tend to be stronger for livestock products than for staple
162 crops (Figure S 12, Figure S 13).

163

164 Regional estimates also deserve specific attention, considering the regional heterogeneity in
165 climate change impacts and vulnerability. In Sub-Saharan Africa and South Asia (India and
166 Other Asia; see Table S 4 for regional definitions), which currently already have the most
167 acute prevalence of hunger (Figure S 14), the prevalence of undernourishment increases by
168 12 and 16 million people in 2050, respectively, on average, across all models in the RCP2.6
169 and SSP2 scenario (Figure 3a). These two regions account for 40% and 20%, respectively, of
170 the global population at risk of hunger under climate mitigation in 2050. Moreover, most
171 models show a great degree of price sensitivity of food demands in low-income regions, as
172 compared with high-income ones (Figure 3b).

173

174 Our findings should not be interpreted to downplay the importance of future GHG emissions
175 mitigation efforts, or to suggest that climate policy will cause more harm than good in
176 general. Instead, this study highlights the need for careful design of emissions mitigation
177 policies in upcoming decades, e.g. targeted schemes encouraging more productive and
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
180 change mitigation policies on vulnerable regions.

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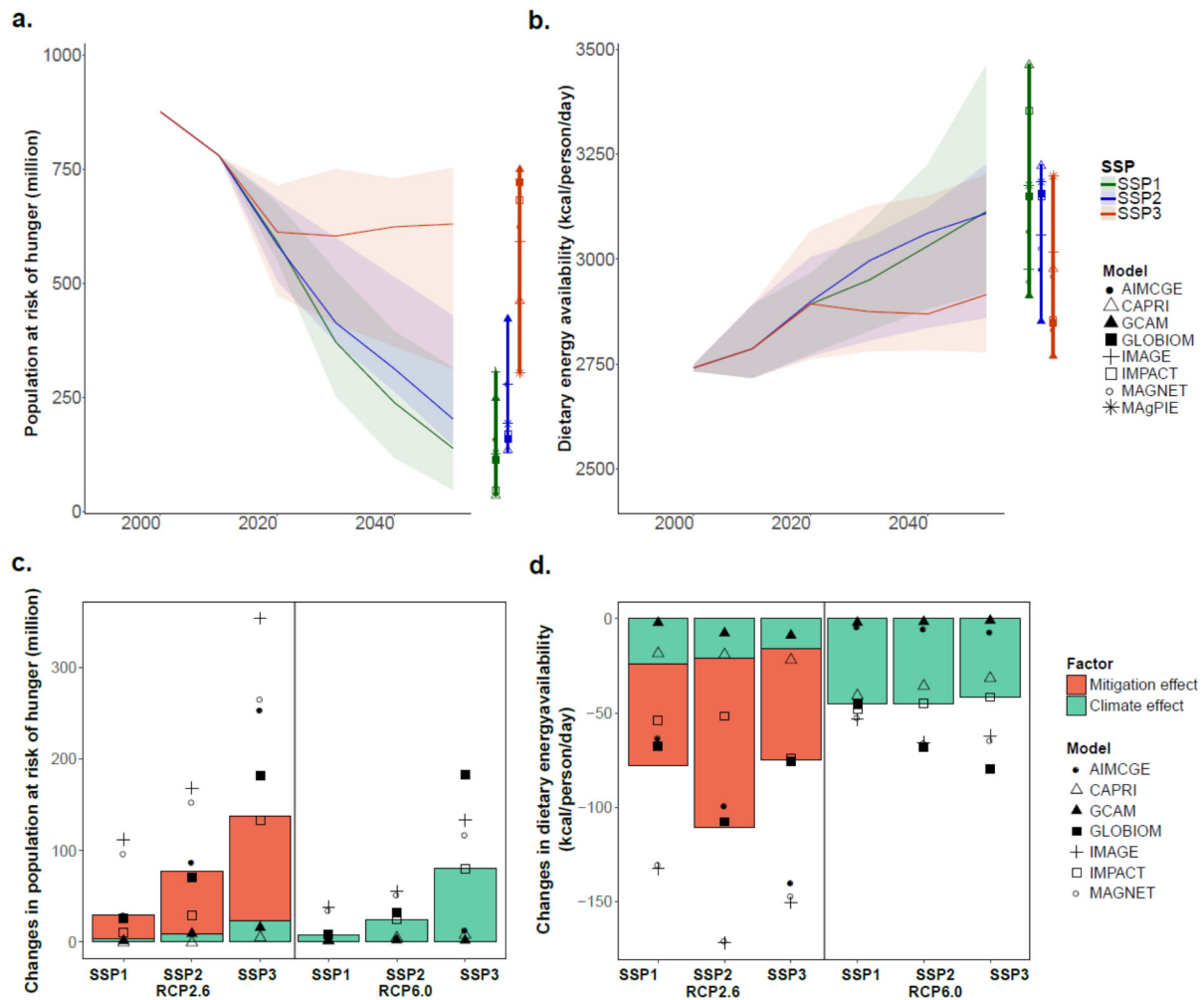
182 Moreover, climate policies can have synergistic effects with food security. For example,
183 taxes on red-meat and dairy-products are expected to cut emissions and improve nutritional
184 health¹⁹. Revenue from carbon taxes would bring a new source of income which could be
185 used for food aid programs in low-income nations. Moreover, production systems in food
186 insecure regions are often less GHG emissions and resource efficient than those in developed
187 countries. For example, the developing world contributes 75% of global GHG emissions from
188 ruminants while it supplies only half of milk and beef²⁰. Thus, the transfer of resource-
189 efficient production technologies, including land- and emissions-saving ones, to developing
190 regions could both contribute to climate mitigation and economic development⁴. 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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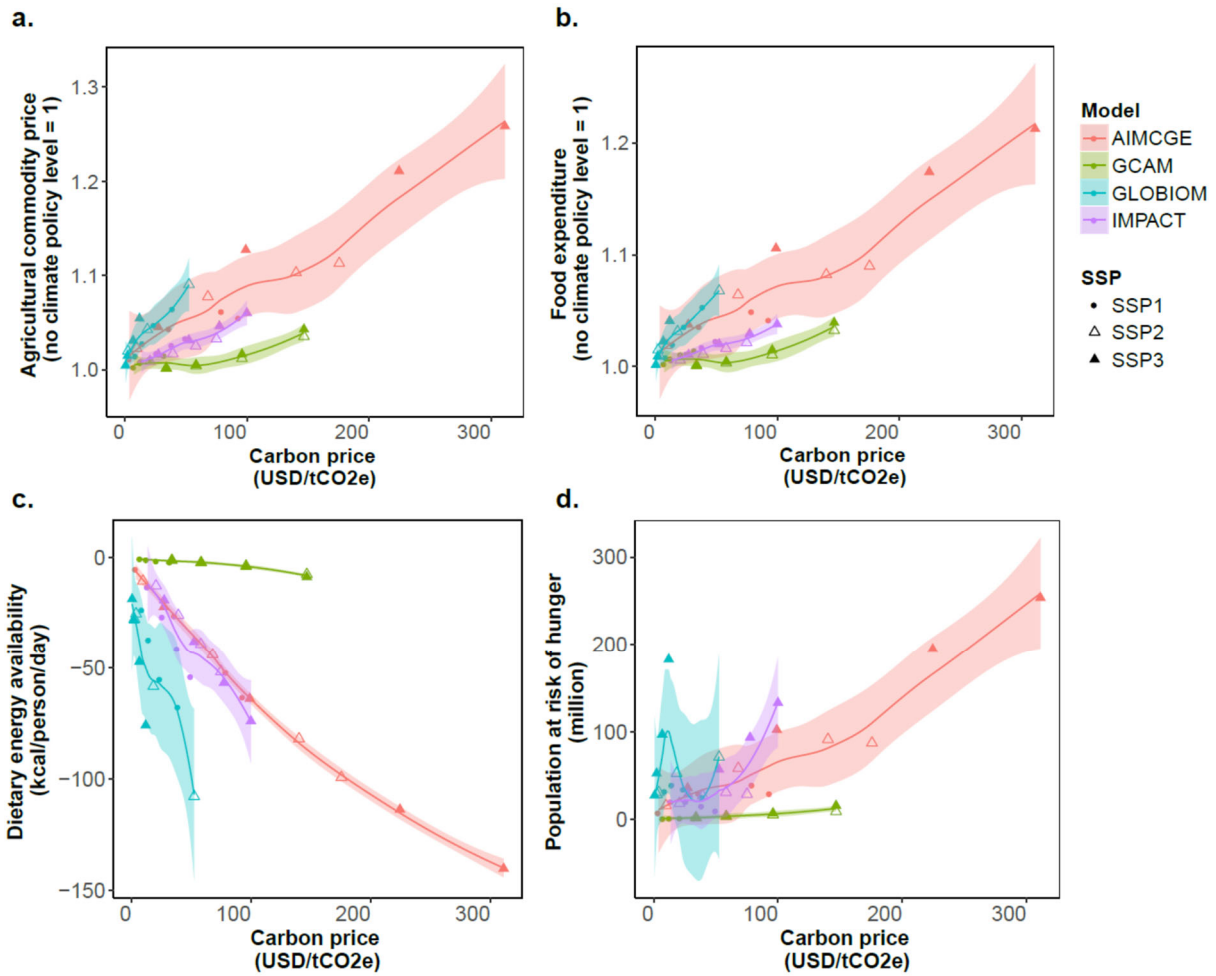
195 Food security is a multi-dimensional and -disciplinary challenge, spanning scales from the
196 global to local levels. In this study, we have focused on analyzing the potential consequences
197 of climate change and emissions mitigation policies on two components of food security
198 (food availability 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
202 mitigate climate change and to reduce hunger, against a backdrop of a changing climate and
203 dynamic socio-economic conditions.

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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.



219
 220 Figure 1 Effects of climate change and emissions mitigation efforts on food security. a)
 221 Global population at risk of hunger and b) global mean dietary energy availability in the
 222 baseline scenario under different socio-economic scenarios (SSPs). Ribbons and error bars
 223 show the ranges across models. c, d) Changes from the baseline level due to climate change
 224 and emissions mitigation efforts under different SSPs and climate change and emissions
 225 mitigation scenarios (RCPs) in 2050. Bars shows median level of individual effect across
 226 models. Symbols show the combined effects for each model. MAgPIE is excluded due to
 227 inelastic food demand.



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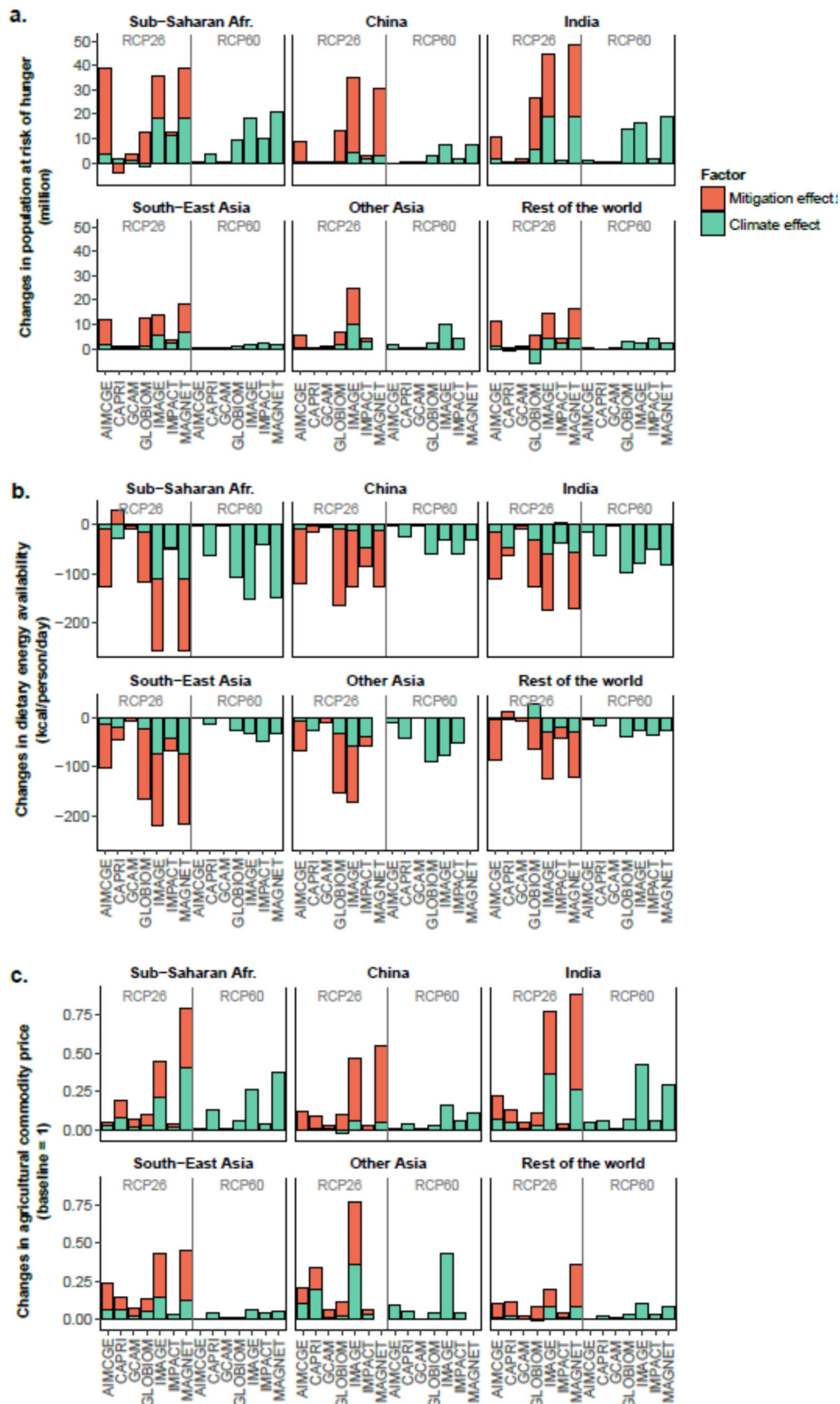
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Figure 2 Relationship between land-based mitigation and food security indicators by 2050 under ambitious climate mitigation scenarios (RCP2.6) with residual climate change impacts for three SSPs. The range shows the 95% confidence level interval. This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



234
 235 Figure 3 Regional effects of climate change and emissions mitigation on a) population at risk
 236 of hunger, b) mean dietary energy availability and c) agricultural commodity price in 2050
 237 under intermediate socio-economic scenario (SSP2). Values indicate changes from the
 238 baseline scenario with no climate change and no climate mitigation. MAGPIE is excluded due
 239 to inelastic food demand. The value of India includes that of Other Asia in MAGNET.

240 **References**

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330

331 **Author Contributions**

332 T.H. coordinated the conception and writing of the paper, performed the scenario analysis and created
333 the figures; T.H., S.F, Y.O. created the hunger estimation tool for the multiple models; T.H., S.F, P.H.
334 and H.V. designed the research, led the writing of the paper and designed the scenario settings, which
335 were developed and contributed by H.L.C., I.P.D. and H.v.M., with notable contributions from T.H.,
336 S.F., K.T., J.T. (AIM/CGE), P.H., H.V. (GLOBIOM), T.F., I.P.D., P.W. (CAPRI), P.K. (GCAM),
337 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
355 in the main text are direct outputs from the models except the population at risk of hunger.

356 Here, we give scenario settings, data used for scenario runs, model representation of climate
357 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 mitigation²¹.

368 The SSPs are representative future scenarios, including both qualitative and quantitative
369 information in terms of challenges in mitigation and adaptation to climate change. For
370 climate change and climate policy dimensions, we utilize four cases: a baseline scenario with
371 no climate changes (NoCC), a climate change scenario where the climate impacts from
372 RCP6.0 was implemented, and climate mitigation scenarios without and with residual climate
373 change impacts. The comparison between baseline and climate change scenarios allows to
374 extract the pure climate change effects (“Climate effect” in RCP6.0). The difference between
375 scenarios with and without climate policy allows assessment of the effects of ambitious
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
378 impacts effects on agriculture at 2°C of warming (“Climate effect” of RCP2.6). For climate
379 condition, we harmonized the exogenous climate impacts on agricultural productivity by
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)
382 and the carbon constrained pathway (RCP2.6) which is often interpreted as a 2°C goal in line
383 with the Paris Agreement⁷ to achieve more than 66% chance to stay below 2.0°C]. RCP2.6
384 and RCP6.0 are the GHG concentration pathways stabilizing radiative forcing at the end of
385 the 21st century at approximately 2.6 and 6.0 W/m², respectively^{22, 23}. RCP2.6 corresponds
386 roughly to a global mean temperature rise from preindustrial times to less than 2°C by 2100
387 while RCP6.0 has a 2.7°C rise. In the SSP scenarios²⁴, most models’ reference scenarios had
388 forcing levels in 2100 of around 7 W/m². Thus, while no-mitigation scenarios are generally
389 between RCP6.0 and RCP8.5, here we have selected RCP6.0 because it is relatively closer to
390 7 W/m².

391

392 **Socioeconomic assumptions and data.**

393 Each model changes socio-economic assumptions such as population, gross domestic product
394 (GDP), dietary preferences, agricultural intensification irrespective of climate change, land-
395 use regulation and international trade according to the SSP storylines¹⁵. All models were run
396 with exogenous GDP and population, which were harmonized across models using the SSP
397 socio-economic data²⁵. In SSP2, the global population reaches 9.3 billion by 2050, an
398 increase of 35% relative to 2010, and global GDP triples. For other characteristics captured
399 by SSPs, the modeling teams made their own assumptions on how to best represent the
400 described future trends. It is expected that model results for the same scenario will differ
401 significantly, due to different interpretations and implementations of the SSP storylines
402 across models. The effectiveness of agricultural technologies (e.g., improved crops, irrigation
403 expansion, changes in trade) and other socio-economic conditions (e.g., population growth
404 and income) can be assessed by comparing results across the SSPs. The models implicitly
405 assume present-day agricultural policies to remain in place through calibration (e.g., price
406 wedges based on statistical data¹²). Although all of the current national agricultural policies
407 and governmental actions were implicitly covered, some of the specific features of these
408 policies, going beyond the relative price difference were not captured. There are some studies
409 considering the current short-term climate targets (e.g. the Nationally determined
410 contributions (NDCs))^{26, 27} or the biofuel policies or mandates (e.g. the U.S. renewable fuel
411 standard (RFS2) or European Union renewable energy targets in the Renewable Energy
412 Directive (RED))^{28, 29, 30, 31}. Although the implementation of these policies is technically
413 possible for the models used in this study, here we focus on the implications of climate
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
416 paper shown in Table S 2.

417

418 **Climate change effects on crop yield**

419 In the scenarios with climate change, we used results of the yield change of up to twelve
420 types of crops (maize, millet, rice, wheat, rapeseed, soybeans, sunflower, other oilseeds,
421 cassava, ground nuts, sugar beet and sugar cane) estimated by using the five global earth
422 system or climate models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-
423 ESM2M and NorESM1-M) contributing to the fifth phase of the Coupled Model
424 Intercomparison Project (CMIP5)³², and three global crop models (EPIC³³, LPJmL^{34, 35},
425 pDSSAT^{36, 37}) that contributed to the ISI-MIP fast-track data archive³⁸. These three crop
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 CO₂
428 fertilization effects. For the mapping of crops simulated in the crop models to commodities
429 used in the economic models, we apply the same methods as prior AgMIP research² (Table
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
432 the global models, the gridded yields were spatially aggregated into country or regional
433 values using the present crop- and irrigation system specific areas based on the Spatial
434 Production Allocation Model (SPAM) data base³⁹. Direct climate change impacts on
435 livestock and fish production are not considered due to data limitation. Since the portion of
436 the global population that is most vulnerable to food security issues tend to rely mostly on
437 crops for food, this assumption would likely not affect change our findings, but further
438 analysis would be required for confirmation.

439

440 **Model representation of climate policy**

441 All models implemented a global uniform carbon price on greenhouse gas emissions across
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
445 and then food price through three channels: (1) putting carbon taxes on agricultural GHG
446 emissions directly increases the costs of production proportional to the GHG intensity of the
447 production¹⁷, and therefore food prices; (2) putting carbon taxes on GHG emissions/sinks
448 from land use change, makes expansion of cropland expensive and hence leads to higher land
449 rents and food prices; (3) putting carbon taxes on the energy sector leads to increased demand
450 for biomass for energy use, which also demands land, pushing land rents upwards. Increase in
451 the cost leads to increased food market prices, which in turn lead to reduction in
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
454 capital, (6) use of carbon capture and storage technology, and (7) implementation of
455 mitigation abatement technologies to reduce emission intensities. Some models (e.g. AIM,
456 GCAM) apply exogenous marginal abatement cost curves to represent technological
457 reduction in emissions intensity of agricultural production, reducing the degree to which the
458 mitigation policies impact modeled prices and production levels. Carbon prices may also
459 induce a shift to a low-emission industrial structure, which, in AIM, will lead to gross
460 domestic product (GDP) losses and decreased wages and household incomes. Consumers
461 respond to the price increase and income loss by decreasing consumption and shifting to less
462 expensive goods. In most models, carbon tax revenue stays outside of agricultural sectors
463 both on producer and consumer sides and is not properly redistributed to affected people.
464 Mitigation options, carbon price, amount of emission reductions in agriculture and land-use,
465 and emissions coverages were not harmonized across models due to the complexity of the
466 models involved (see for carbon price and the fraction of GHG reduction in Figure S 8). See

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

469

470 Our results illustrate how the approach chosen here for implementing emissions mitigation—
471 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
473 has been shown to require much larger and often very costly emissions reductions from the
474 balance of the system, and for ambitious mitigation targets (e.g. 2 °C), significant exemptions
475 to the policy may put the mitigation goals out of reach^{40, 41, 42, 43, 44}.

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478 **Baseline (non-climate related) agricultural productivity changes**

479 Baseline (non-climate related) agricultural productivity changes (e.g. from research and
480 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 irrigation⁴⁵.
483 Figure S 10 reports the resulting yield changes between 2005 and 2050 for selected crops in
484 selected countries that exclude the impacts of climate change. To calculate those impacts on
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**

489 All of the models have in common that they contain agricultural markets with different
490 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
493 income growth increase food demand, shift the demand curve rightward and raise prices.
494 Responding to the higher price, producers increase their production through expanding crop
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
498 reallocate supply and demand, decreases food prices and contributes to a lower risk of
499 hunger. In the same way, decreases in crop yields due to climate change shift the supply
500 curve leftward, thus decreasing food supply, raising prices, and resulting in the same
501 responses to the high price.

502

503 Agricultural commodity prices are endogenously determined under the supply and demand
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
506 precise harmonization. For supply side, the models represent dynamic changes in production
507 cost and inputs. Economic growth increases resource-use efficiency and labour productivity,
508 which in turn contributes to decreased crop production cost and price. High pressure on land,
509 which is one of the inputs to agricultural production, eventually leads to high land rent and
510 raises prices. For the demand side, the given population and income growth boost food
511 demand based on income elasticity either implicitly or explicitly represented in each model,
512 shifting the demand curve rightward and thus raising prices. Under a climate policy, the
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
515 bioenergy deployment disincentivizes the use of land for food crop production, thereby
516 increasing land rent and crop prices.

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Methods to estimate the population at risk of hunger

To project population at risk of hunger, we adopt an implementation of the FAO’s approach⁴⁶ 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 nutrients⁴⁸. 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 level⁴⁹, adjustment coefficient for the MDER in different age and sex groups⁵⁰ and the future population demographics²⁵ 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.

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