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FRONT MATTER

Title

Inclusive climate change mitigation and food security policy under 1.5°C climate goal

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Abstract

Climate change mitigation to limit warming to 1.5°C or well below 2°C, as suggested by the Paris Agreement, can rely on large-scale deployment of land-related measures (e.g., afforestation, or bioenergy production). This can increase food prices, and hence raises food security concerns. Here we show how an inclusive policy design can avoid these adverse side-effects. Food-security support through international aid, bioenergy tax, or domestic reallocation of income can shield impoverished and vulnerable people from the additional risk of hunger that would be caused by the economic effects of policies narrowly focussing on climate objectives only. In absence of such support, 35% more people might be at risk of hunger by 2050 (i.e. 84 million additional people) in a 2°C-consistent scenario. The additional global welfare

changes due to inclusive climate policies are small (<0.1%) compared to the total climate mitigation cost (3.7% welfare loss), and the financial costs of international aid amount to about half a percent of high-income countries' GDP. This implies that climate policy should treat this issue carefully. Although there are challenges to implement food policies, options exist to avoid the food security concerns often linked to climate mitigation.

MAIN TEXT

Introduction

The Paris Agreement defines a long-term temperature goal for international climate policy: "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Furthermore, the Paris Agreement outcome also sets milestones for future international climate policy, for both the near (up to 2030) and the long term (mid-century to century scale) [1, 2]. Many studies exploring climate change mitigation policies consistent with the Paris objectives have identified a potential need for large-scale land-related measures like afforestation and large-scale bioenergy crop production [3, 4], which would play a critical role in generating negative CO_2 emissions. Moreover, efforts are also required on the direct non-CO_2 emissions from agriculture [5]. Because of their link to land and food production, these measures can raise concerns about their potential implications for food security [6].

The global number of people at risk of hunger has steadily declined over the past decades and was estimated at 795 million[7] for the year 2015 which is 184 million less than 1990-1992 (979 million), despite a significant population increase in low-income countries [7]. Facing risk of hunger in this context represents a state lasting at least a year of inability to acquire enough food below the minimum dietary energy requirement within a food distribution. Relatively stable political conditions and economic growth mainly contributed to this trend. More than 60% of the global risk of hunger is occupied by Sub-Saharan Africa and Southern Asia. For the future, long-term food security has been intensively studied within the context of climate change impacts [8-10], and more recent studies also explored the effect of climate change mitigation on agricultural markets [11-15]. Despite differing scenario assumptions, metrics, and quantitative outcomes, these studies qualitatively agree that naïve mitigation policies such as simply pricing greenhouse gas (GHG) emissions could increase prices of agricultural commodities because GHG emissions generated in the production of these commodities are penalized by a GHG price. Such policies can hence adversely impact food security in developing countries. This thus begs the question whether counter-measures exist which can overcome and avoid these potentially unfavorable side effects of stringent climate mitigation, and how this trade-off could play out in the context of the Paris Agreement. Although a few studies investigate the relationship between future climate mitigation policy and food security [11, 14], two crucial aspects remain currently unexplored: first, which policy designs allow to eradicate the negative side-effects of climate policy in long-term mitigation scenarios, and, second, how do food security concerns play out in the context of Paris Agreement, and more specifically, when taking into account the current NDCs (Nationally Determined Contributions) and while pursuing a 1.5°C goal?

To fill this gap, we here explore the potential consequences of a global 1.5°C climate policy on food security, and formulate inclusive policy designs that shield people from the risk of hunger. We focus mainly on food security support policy (through either international support or national redistribution) as an illustrative simple example of possible policy instruments. Other instruments, including demand expansion, market differentiation, producer price supports [16] can be applied as well, and would influence the quantified policy costs.

Method

We use the AIM (Asia-Pacific Integrated Model) modeling framework [1, 17]. Our modeling framework includes land-based mitigation options such as bioenergy crops, afforestation, and non-CO_2 emissions reductions. The land-use change emissions are also represented by changes in the forest area and carbon density.The core of the AIM framework for this study is AIM/CGE (Computable General Equilibrium) that models interactions among energy, agriculture, and land use markets as well as climate mitigation and food security policy to explore long-term market interactions (model documentation is available online [18]). We use the number of people at risk of hunger as a metric of food security (see Supplementary Text 1, 2). Although our calculation of risk of hunger is based on an approach developed and used by the FAO which makes simplified assumptions about food distributions within countries, this indicator is currently the most widely used for food security assessment[19] in many large scale assessments with regional implications [20, 21] as well as a sustainable development goal (Goal 2).

We develop scenarios which cover three dimensions as shown in a table in Supplementary Information Table S 1: 1) varying future socioeconomic assumptions, 2) varying stringency of climate change mitigation policy, and 3) different inclusive food security policies. Food security strongly depends on the socioeconomic assumptions [22], and we hence verify the robustness of our results with respect to various socioeconomic developments. Varying levels of climate change mitigation stringency allow us to identify whether trade-offs are specific to 1.5°C or 2 °C scenarios, which can be of interest to policy discussions. Finally, different designs of food security policies allow us to explore their effectiveness in canceling out trade-offs (see futhre below).

To explore the socioeconomic uncertainty, we use Shared Socioeconomic Pathways (SSPs) that depict five future plausible representative evolutions of key socioeconomic characteristics that vary along two dimensions: challenges to mitigation and adaptation. Three SSPs (SSP1, SSP2 and SSP3) are chosen for this study and they are referred to as “sustainable development”, “middle of the road” and “regional rivalry”, respectively. From a climate change mitigation point of view, the challenges to mitigation is increase going from SSP1, over SSP2, to SSP3.(for details on assumptions, see Supplementary text Methods).

We consider four mitigation levels: no climate policy (baseline), GHG emissions reductions by 2030 in line with the NDCs, and scenarios that limit global mean temperature in 2100 to below 2°C and 1.5°C in which cost-effective emissions reduction are assumed from in 2020 onwards. GHG emissions until 2050 are illustrated in Fig. 1**a** (Supplementary Fig S. 1 **a** for all SSPs and emissions until the end of the century). The baseline does not include any climate policy which means zero carbon price is assumed. Moreover, neither currently planned or implemented energy and land use policy are excluded. Basically, climate change mitigation ignoring food security concerns makes food prices increase as a carbon price is imposed on non-CO_2 emissions from the agricultural sector, and as land rent increases driven by energy crop and afforestation demand. Overall income loss due to the costs of mitigation also affects to the food consumption.

Our various ‘inclusive’ climate policy designs attempt to simultaneously accomplish both climate and food security objectives. To explore this, we model four types of food security policies by including: (1) international aid, (2) domestic reallocation, (3) a bioenergy tax, and (4) exempting agricultural non-CO_2 emissions from being priced with a carbon tax. The intent of each of these policies is to eradicate possible negative side-effects of mitigation for the risk of hunger (but can also fail to achieve these, as illustrated below).

Our ‘international-aid’ option reflects the possibility of international donors providing funds to shield poor populations from the potential impacts of mitigation measures through a re-distribution of funds. In our ‘domestic reallocation’ option, income is reallocated within the region. The redistribution of income between households decreases the consumption of non-food goods and services in favor of fulfilling food demand. Since households in our model are modelled through a single representative household for each region, the redistribution of income among households decreases the consumption of non-food goods and services in favor of fulfilling food demand. In the model we have added a constraint on the household food consumption (equal to the consumption in baseline) which is matched with an endogenous variable to adjust the parameter of the household consumption function as mixed complementary problem. We interpret this policy as a sort of income redistribution or transfer from the wealthier to the poor where the non-food consumption of rich populations is used for food consumption of the poor. Our "bioenergy-tax" aims to obtain tax revenue to supplement the food deficit and to suppress excessive bioenergy increase. Exempting agricultural non-CO_2 (CH_4 and N_2O) emissions avoids that the agricultural sector and its production is burdened by a carbon tax penalty and hence also avoids the impact of climate mitigation policy on food markets The international-aid option is a straightforward redistribution policy, which, for example, currently already exist as Official Development Assistance (ODA). The domestic-reallocation would also be a part of income redistribution system (e.g., progressive taxation). More detailed information about these policies is available in the Supplementary text Methods section. Policies can also be combined, but in this study, we chose to keep to the four illustrative designs which were introduced above, as they have proven sufficient for deriving the conclusions of this study.

Yield change effects caused by climate change (e.g., due to temperature and precipitation changes) have been excluded in this study, so the focus is solely on the policy impact of mitigation measures on food security. The main reason for this is the relatively short time horizon of this study (until 2050). Several reports, some using the same modeling framework as this study, have indicated that the climate change impacts on food and agriculture would be relatively small on average for this time scale [11, 23] compared to mitigation effect. The more recent study also shows similar results [24, 25]. We compared the scenarios with climate change impact yield shock and the climate mitigation which shows that mitigation effect is significantly higher than the climate change impact at the end (Fig S. 2). However, the local and long-term climate change impact could be more serious than the mitigation effect. Since our primary goal is to get global insights, further studies that focus on regional or local scales would supplement this study in the future.

Results

Evolution of people at risk of hunger

The number of people at risk of hunger is projected to decline in our middle-of-the-road (SSP2) baseline scenario, from 795 million in 2015 to 238 million in 2050 (thick green line in Fig. 1**b**). This declining trend is a continuation from the last two historical decades. Looking further into the future after 2050, the risk of hunger declines to almost zero in all SSP2 scenarios, including those with stringent mitigation (Supplementary Fig S. 1**b**). The primary driver of this decline is income growth in developing countries. Over the course of the century, however, significant populations at risk of hunger remain and differences between scenarios with varying climate change mitigation stringency exist. Simulations in which policies target mitigation but ignore potential adverse side-effects, show a potential increase in the risk of hunger (Fig. 1**b**-**c**) until mid-century. Without policies that are designed to balance and remediate adverse side-effects, the risk of hunger can be respectively 1.6 and 1.4 times larger in 2050 in scenarios pursuing a 1.5°C or 2°C goal compared to the baseline. This corresponds to 369 and 322 million people, respectively, at risk of hunger. Since the risk of hunger already declines strongly under baseline assumptions until 2050, the incremental number is also smaller. Exposure to risk of hunger is thus a transient issue in our model setup which disappears by the end of the century, but demands particular attention in the first half of this century.

Consistent with existing estimates [2], our NDC scenario results in comparatively modest emissions reductions. In absence of climate impacts affecting the risk of hunger in our framework, its policy impact on food security is hence relatively limited compared to the abovementioned more stringent mitigation cases. A food-climate-economy triangle can represent the climate change and food security objectives, as well as the associated costs of reaching these goals for different policy cases (Fig. 1**d**). A narrow-minded approach towards achieving mitigation goals (which simply targets emissions and ignores food security interactions) sees an increased potential for people being at risk of hunger, increasing mitigating costs with increasing stringency of mitigation, and corresponding lower levels of global warming. Consistent with what is generally assumed in assessments of international climate goals, the median temperature change in 2100 for 1.5 and 2°C scenarios is below the nominal scenario value because scenarios are designed to achieve an objective with at least 66% probability. In this case the median temperature increase in 2100 is estimated at around 1.3°C and 1.7°C, respectively.

When climate policies ignore food security issues, the risk of hunger increases through two main mechanisms: an increase in food prices and a decrease in income. The price effect is larger than the income effect (Fig. 2**a,b**, and Supplementary text for a decomposition analysis). For example, 88% of the risk-of-hunger increase can be attributed to the price effect in our SSP2-1.5°C scenario. Although income loss accounts to several percentage points (but no more than 5% in SSP2, Fig. 2**d**), the corresponding food price changes are an order of magnitude larger (see Fig. 2**c** and Supplementary Fig S. 1). Given relatively similar price and income elasticities (see Supplementary Data 1), the size of these price shocks ultimately results in a decrease in food consumption in our framework. Income loss in our scenarios is associated with investment costs to decarbonize the energy system and investments in other non-energy related emissions abatement. Lastly, food price changes are mainly caused by land competition with bioenergy crops whose demand is correlated in our model with the stringency of mitigation, as well as by the non-CO_2 greenhouse gas (GHG) emissions of the agricultural sector which are also subject to the overall GHG price (Fig. 2**e**,**f** and Supplementary Fig S. 3). Non-CO_2 GHG emissions are partly abated, but significant residual emissions remain even in stringent mitigation scenarios (see Supplementary Fig S. 1**g**,**h**).

Inclusive climate change mitigation policy

The potential evolutions of the number of people at risk of hunger indicate the need to consider climate and food security policies together (Fig. 3). When no complementary food security policies are considered, the expected trade-offs between climate change mitigation and food security are obviously largest (see "No" case in Fig. 3). Policy designs which consider international-aid and domestic-reallocation ("Int" and "Dom" in Fig. 3) are most effective to simultaneously achieve climate and food security goals, as they are able to eradicate all the potential side effects of climate change mitigation on food security while still meeting the temperature targets. In economic terms, this comes at very small total economic costs. Regardless of whether food security policies are implemented or not, Total global economic losses associated with food security policy (accounted as additional welfare changes relative to the policy case without a food security policy) are quite small, as illustrated by the bottom-right vertexes in the triangles in Figure Fig. 3**a,c**. In contrast, the distribution of regional economic effect between high and low-income countries can vary strongly (Fig. 3 **b**,**d**).

In our international-aid case, the welfare loss is largest in OECD countries amounting to 0.5% of welfare under the 1.5 °C scenario. Concurrently, low-income countries gain welfare (0.5%). These values can be compared with current levels of Official Development Assistance (ODA), which is 0.32% of GNI (Gross National Income) in developed world. Implementing international aid food security would result in comparable amounts of aid[26]. (More detailed regional welfare changes are in Supplementary **Fig S. 4**). Furthermore, climate mitigation costs are much larger than the food security policy costs (3.7% of welfare). In the case food security concerns are tackled by a domestic-reallocation policy ("Dom") the regional distribution response is much smaller (Fig. 3 **b**). These economic indicators have to be seen together with institutional and ethical considerations (see Discussion section).

Attempting to reduce the potential trade-offs between climate mitigation in food security by not pricing agricultural non-CO_2 emissions ("NonAgr" in Fig. 3) only has a small effect, and 352 million people remain facing at risk of hunger while attempting to achieve a 1.5 °C goal. Also, the climate outcome is worsened in this case compared to the "No" food security policy case, because non-CO_2 emissions can increase. This leads to 0.3 °C higher warming compared to the "No" case, leaving both climate and food security objectives unaccomplished. Taxing bioenergy production ("Bio") performs slightly better than the "NonAgr" case regarding food security and the achievement of climate goals. This case meets the climate goal, but an additional 20 million people remain at risk of hunger while bioenergy supply is suppressed by the tax (see Supplementary Fig S. 5**a**).

For the 2 °C cases, similar trends are found for all inclusive-policy designs. Only the magnitude is smaller (Fig. 3 **c**,**d**). For example, International-aid generates 0.24% welfare loss in high-income countries achieving both climate and food security objectives. While complementary policies can change the food security situation, the overall energy and land-use evolutions are unchanged from the case without food security policies (see Supplementary Fig S. 5**ab**).

Socioeconomic development diversity and its consequences

Variations in socioeconomic development patterns can impact the number of people at risk of hunger. We therefore explore whether the inclusive policy packages introduced above could be equally effective in eradicating food security trade-offs across three diverse socioeconomic futures represented by the SSPs. Socioeconomic variations amplify the differences of climate mitigation cost and the food security among the scenarios. For example, in the baseline of a green-growth world (SSP1), the number of people at risk of hunger is reduced to 110 million in 2050, while in a fragmented world (SSP3) it increases to 638 million (Supplementary Fig S. 1**b**, compared to 238 million people in SSP2). These variations between the scenarios are due to differences in population, per capita food consumption level (mostly driven by income growth), and food consumption distribution assumptions. Based on a sensitivity analysis, we identified that GDP and population assumptions are the key drivers of the differences in the number of people at risk of hunger across SSPs (more details in Supplementary Text 3). Looking at the absolute magnitude of these inter-scenario variations, provides a much more diversified image of the potential trade-offs between climate mitigation policy and food security (Supplementary Fig S. 1**b**). In particular, in the SSP3-2 °C case, the risk of hunger increases throughout this century and reaches almost 1500 million in 2100. The mitigation cost for 2 °C in such a heterogeneous world (SSP3) are estimated at 6% of global welfare loss, and are particularly high in 2050. In contrast, the mitigation costs for 1.5 °C in a green-growth world (SSP1) are estimated at 3.5%, roughly half of the SSP3 costs for 2 °C (Supplementary Fig S. 1**e** and **f**). The relative change in the number of people at risk of hunger is quite constant across three socioeconomic worlds (around 1.5-fold in 2 °C scenarios). Similarly, the decomposition analysis shows that the income and price factors change the risk of hunger similarly across three SSPs (Fig. 2**a**). Lastly, in our green-growth world (SSP1), the number of people at risk of hunger is small, and the complementary policy welfare change is small accordingly (Supplementary **Fig S. 6**). Concurrently, in our heterogeneous world (SSP3), the potential of narrow mitigation policy is much larger and efforts to eradicate these side effect thus become much more important.

Spatial distribution of hunger and financial requirements

Regional estimates provide an additional dimension to our risk-of-hunger assessment. In our SSP2 baseline scenario, the risk of hunger steadily declines in all regions in parallel with the global trend. The relative importance of regions in 2050 changes slightly compared to today, but it remains similar overall (Fig. 4, green bar). Sub-Saharan Africa and South Asia (Rest of Asia) remain risk-of-hunger hotspots, also under diverse socioeconomic worlds (Supplementary Fig S. 7). Moreover, the geographical distribution of potential adverse side-effects of mitigation correlates with the regional risk of hunger in the baseline (Supplementary Fig S. 8). This indicates that regions having a relatively high risk of hunger in the baseline are also hotspots for potential adverse side-effects in mitigation scenarios. For instance, Sub-Saharan Africa and South Asia have 47% and 19% of the global share in population at risk of hunger under the baseline scenario respectively (Fig. 4), compared to 48% and 16%, respectively, in the 1.5°C scenario. The food consumption probability distribution illustrates these regional dynamics (Supplementary Fig S. 9). From the base year to 2050, mean food consumption increases and the equity of food distribution improves as the distributions shift rightward and become sharper. However, the mean level is reduced by mitigation.

The required financial flows vary across regions. Bubbles in Fig. 4 illustrate the financial flow for our international aid policy case. Since we here assume donors to provide financial aid equal ratio to GDP to developing world (e.g. X% of GDP goes from all donors), the scale of the financial aid for donors across regions is same (the empty circles). Regions that represent a hotspot in terms of food security trade-offs demand financial aid, for example, Sub-Saharan Africa. Brazil shows a relatively high food policy cost (measured in relative terms) although the absolute number at risk of hunger is small compared to other regions. It is mainly because Brazil has high inequality in food consumption distribution which requires a higher intervention in the food price.

Discussion

Our findings provide information on international climate change and sustainable development policy. We show that there is a connection between climate and food security policy which increases in importance with the stringency of the mitigation efforts. Here we would like to emphasize that inclusive climate policy packages can achieve stringent climate goals without adverse food security effects by aligning and including appropriate food security measures. Providing solutions in the form of well-designed policy packages should be a priority for research aiming at identifying trade-offs between societal objectives. Importantly, the incremental food security policy cost is much smaller than mitigation cost and the inclusive mitigation policy packages would barely change net global total welfare, whereas the geographical distribution of the cost depends on the design of food security policies and can sometimes have large regional implications for specific regions or cases.. Some policies affect the welfare distribution (e.g., international aid) and some do not (e.g., domestic reallocation). General socioeconomic developments play an important role. Socioeconomic variations as captured by the baselines of three SSPs which represent a green-growth (SSP1), middle-of-the-road (SSP2), and very heterogeneous world (SSP3) can lead to variations in the absolute number of people at risk of hunger which are about 5 times larger than the variations induced by stringent climate policy to achieve a 1.5 °C goal.

It is important to note that our policy packages are meant to be illustrative archetypes of policy designs with different implications for the distribution of costs and associated measures. The scenario exercise in this study adopts simplified policy framework to show the examples of the solutions to the trade-off to understand the basic mechanism and order of the magnitude of incremental policy cost. Our primary goal is to claim that we should have a careful treatment in the climate policy. The policy packages are thus not intended to be exhaustive of all possible potential policies and designs that could be implemented at different scales, for example, food stamps, supplementary feeding program and food-for-work schemes in the food assistance programs [16]. Transaction costs, political constraints, lack of appropriate institutions and governance may render the implementation of some of the policies challenging and require the consideration of local institutional and governance context. Moreover, as for international aid, it would require donor commitments, proper monitoring and code of conduct which have more or less implementation challenges [27]. Nevertheless, our results show that aligning food security and climate objectives is in principle possible across a wide range of socioeconomic pathways, but will greatly depend on the policy design.

Regarding the food policy, there should be some discussions of the interpretation of these food policies. For the international-aid, there are at least four points which should be highlighted here. First, if countries depend on long-term food aid, there could be an adverse side-effect. The aid receiving countries are vulnerable to sudden foreign policies changes. Second, the required financial volume of the cash-based food-aid could be sensitive to the food price and can be volatile, whereas cash-based transfer has great merits compared to traditional food aid (e.g. in-kind food transfers). Third, the aid could demotivate to develop an agricultural technological improvement in those countries, although there are both sides of the argument in the literature that do and do not support this disincentive effect [28, 29]. Fourth, our food-aid policy increases food demand in developing countries to compensate the food demand decreases caused by single-minded climate change mitigation, and the incremental production are mainly produced by developing countries which is domestic goods (see Supplementary Data 3). It can be useful for local farmers that the policy which regulates the incremental food production should be produced domestically because it can increase the opportunity to earn more income of low-income household. We have experimented such scenarios under international-aid policy cases as a sensitivity analysis by incorporating endogenous agricultural subsidy so that the agricultural production is kept the same as the baseline case in SSP2. The results indicate that the welfare would be almost the same as the original international aid policy case while local food production increases production, which could eventually contribute to the local capacity building and have further synergy effects. Therefore, such cash-based aid in conjunction with local production subsidy policy could be one of the alternative policy instruments.

As for domestic distribution policy, one can think that it is difficult to implement such policies in reality. However, there are a number of instruments that transfer income either directly or indirectly, and our proposal is to strengthening such policies. A prime example is the progressive income tax and its transfer to the poor, which has been implemented, although the stringency of progressiveness should differ across countries [30]. Sector-specific examples would be much more diversely implemented. For example, the Colombian massive gas-application program from 1997 to 2009, where higher income households, commercial and industrial users paid a surplus on the full cost of the public service, while part of these funds were used to subsidize the cost for the lower income users *[31]*. The other positive experience of direct cash transfers for poverty is for the energy access to clean cooking in China [32].

There may be various alternative policies besides explicit cash-based transfer. For instance, enhanced agricultural yield growth (e.g., via investment in R&D) would be another option to supplement to offset the risk of adverse side effect. We examined a hypothetical scenario where the yield is assumed to be increased by 50% more than the non-food policy case in 2050 low-income countries (as shown in Supplementary Fig S. 10). In these scenarios, the number of people at risk of hunger in 2050 under 1.5 and 2 °C can be 288 and 253 million which corresponds to 81 and 68 million reductions compared to the reference case (see Supplementary Fig S. 10). From, this experiment, although we cannot identify the cost of such a policy here, enhancing the yield development intending to narrow the yield gap could be one of the alternative measures or can be combined with other food policies.

An argument can be raised that the food price increase possibly reduce poverty [33]. However, this study's price increases differ from the general high food price situation where the increase of price can be attributed to wages. First, the carbon price is imposed on the non-CO_2 emissions, which is not the farmers' income. Second, land competition between food, bioenergy, and afforestation increases land rent which is not always attributed to poor people but often to rich land owners [34]. Third, the climate mitigation measures generate macroeconomic income reduction which cannot be ignored as shown in Figure 2. Therefore, the food price does not necessarily contribute to reducing poverty and risk of hunger.

Because food income elasticity is less than 1, it could be better that decisions about how cash-based food-policy aid is used are taken at the household level because this flexibility would allow them to maximize their welfare[16]. However, since the scope of this study is to show the effect of mitigation policy on the food security and solutions to their trade-off, the aid or transferred money is supposed to be spent only on food purchases and not for other basic needs such as shelter, water and energy. Nevertheless, in the context of general poverty eradication, how to use the redistributed income or aid is a fundamental issue which should be worthwhile to address in future studies.

There is possibly a discussion on the fossil fuel prices which are lower in the mitigation scenarios than those in the baseline scenario (shown in Supplementary Data 2). This can adversely affect the fossil fuel exporting regions (e.g. the Middle East) which consequently causes macroeconomic losses. Meanwhile, it can be a benefit for the low-income fossil fuel importers regardless of applying fuel taxes [35]. However, this benefit is not sufficient to increase their income in the climate mitigation scenarios. There are at least three reasons. First, the income decreases effect associated with GHG emissions reduction are much more prominent than such resource trade condition changes effect. Second, fossil fuels are no longer cheap options due to the high carbon tax imposition. Third, the fossil fuel consumption becomes significantly lower than the baseline scenario to reduce CO_2 emissions.

Although we consider the overall insights from our study to be robust, there are several caveats that are nice to be addressed in the different study. Quantifying how food security and climate interact (i.e., how yields change with climate change and extreme events) is essential and beneficial. At the same time, current climate models do not well represent extreme events, and hence the required climate and yield change data to assess the climate change impacts of these events are lacking at the moment. With improved climate models and data, future assessments should incorporate associated yield changes and their effects on food security. However, we presume that our most valuable insights – that inclusive policy packages can achieve both food security and stringent climate change mitigation – will still hold. The inclusion of micro-nutrition could cover an additional important aspect of food security [36], assessing quality and composition of food rather than the just risk of hunger defined as the number of calories available, as used in this study. If our analysis would be run by other IAM frameworks, the results can slightly differ. For example, other, more technology-focused IAM frameworks commonly project lower mitigation costs than ours which can result in a smaller income effect. At the same time, in our framework non-CO_2 emissions from the agricultural sector can be reduced to a larger degree by the mid-century than in most other modeling frameworks, resulting in a relatively lower pressure from the GHG pricing. Finally, the household disaggregation by income classes or occupations in the modeling framework may bring us the further possibility to investigate more details of income re-distributional policy [37]. These potential further methodological enhancements are not expected to change the macro level insights obtained in this study. They open many interesting avenues for future research.

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SF, TH, VK, and KR designed the research; SF carried out simulation, with inputs from TH and XS; SF carried out the analysis of the modelling results; SF and JR led the writing of the paper; SF created figures; all authors contributed to the discussion and interpretation of the results.

Data Availability:
All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Conflict of interest:
The authors declare no competing financial interests.

Figures and Tables

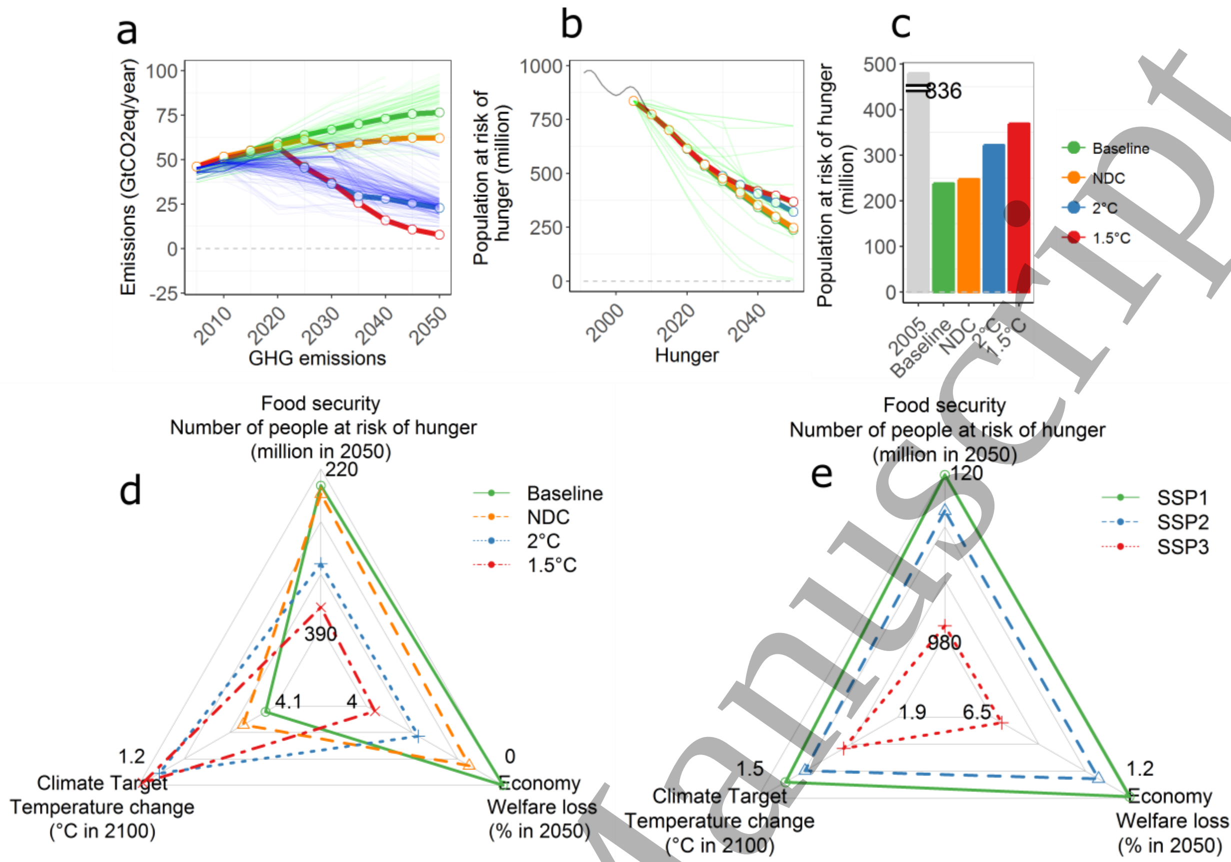

Fig. 1 | Emissions and population at risk. Global GHG emissions (panel a), population at risk of hunger (panel b), comparison of population at risk of hunger in the year 2050 SSP2 (panels c), and food security, climate and economy triangle across climate targets under SSP2 (panel d), and across SSPs under 2°C scenarios (panels e). The indicators shown in panel d and e are measured by the number of people at risk of hunger in 2050, temperature change in 2100 compared with the preindustrial level and welfare loss relative to baseline. All scenarios are excluding additional food policy cases. Thin lines in panels **a** and **b** are literature values (summarized in Hasegawa et al.[22]). Thin green and blue lines in panel **a** are baselines and 430-480ppm CO_2 equivalent concentration stabilization (equivalent to keeping warming to below 2°C) scenarios, respectively, from the WGIII contributions to the IPCC Fifth Assessment Report. Historical value in panel **b** is from FAO[7].

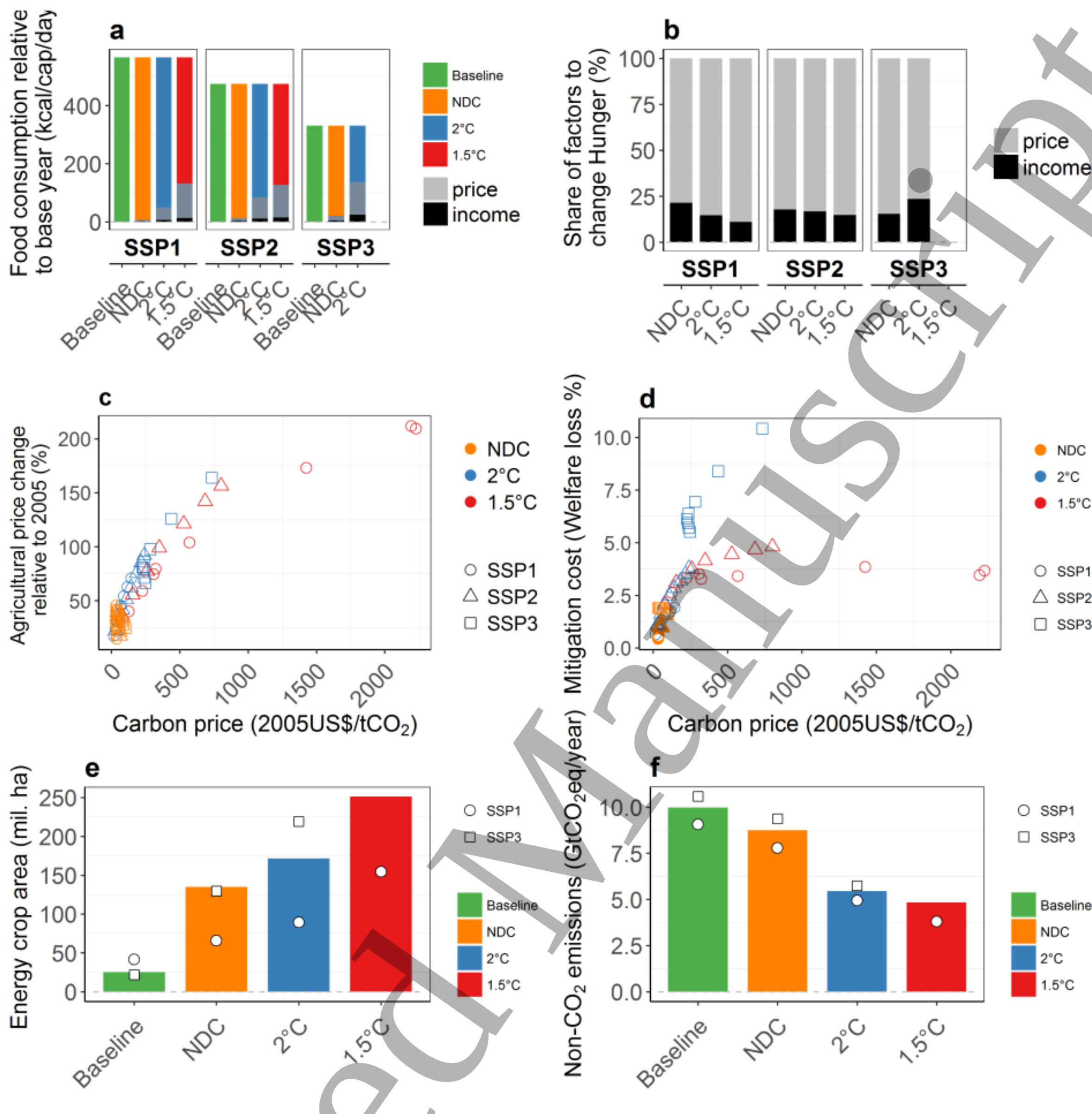

Fig. 2 | Decomposition of food consumption decrease and risk of hunger, and related figures. a, b, e, and f panels show total global values for the year 2050, and **c** and **d** plots every five-year values from 2030 to 2070. **a,** Global mean food consumption accounted as per capita caloric intake per day, relative to the food consumption of 2500 in the base year (x-axis = 2500kcal/cap/day). The black areas indicate the food consumption decreases caused by income losses associated with climate mitigation cost. The gray areas represent food consumption decreases associated with the increase in the price of agricultural commodities due to land competition and non-CO_2 emissions pricing; **b**, The share of income and price effects for the increasing people at risk of hunger for global average; **c**, Relationship between carbon price and food price change. The food price index is produced by using the weighted average price across regions and commodities, Food consumption is used for weighting across regions. Relationship between carbon price and mitigation cost measured by welfare loss rates; **e**, Energy crop area. The bars indicate the values for SSP2 and other SSPs are plotted as a circle and square; **f**, Non-CO_2 emissions (CH_4 and N_2O) from the agricultural sector. The bars indicate SSP2 and other SSPs are plotted as circle and square.

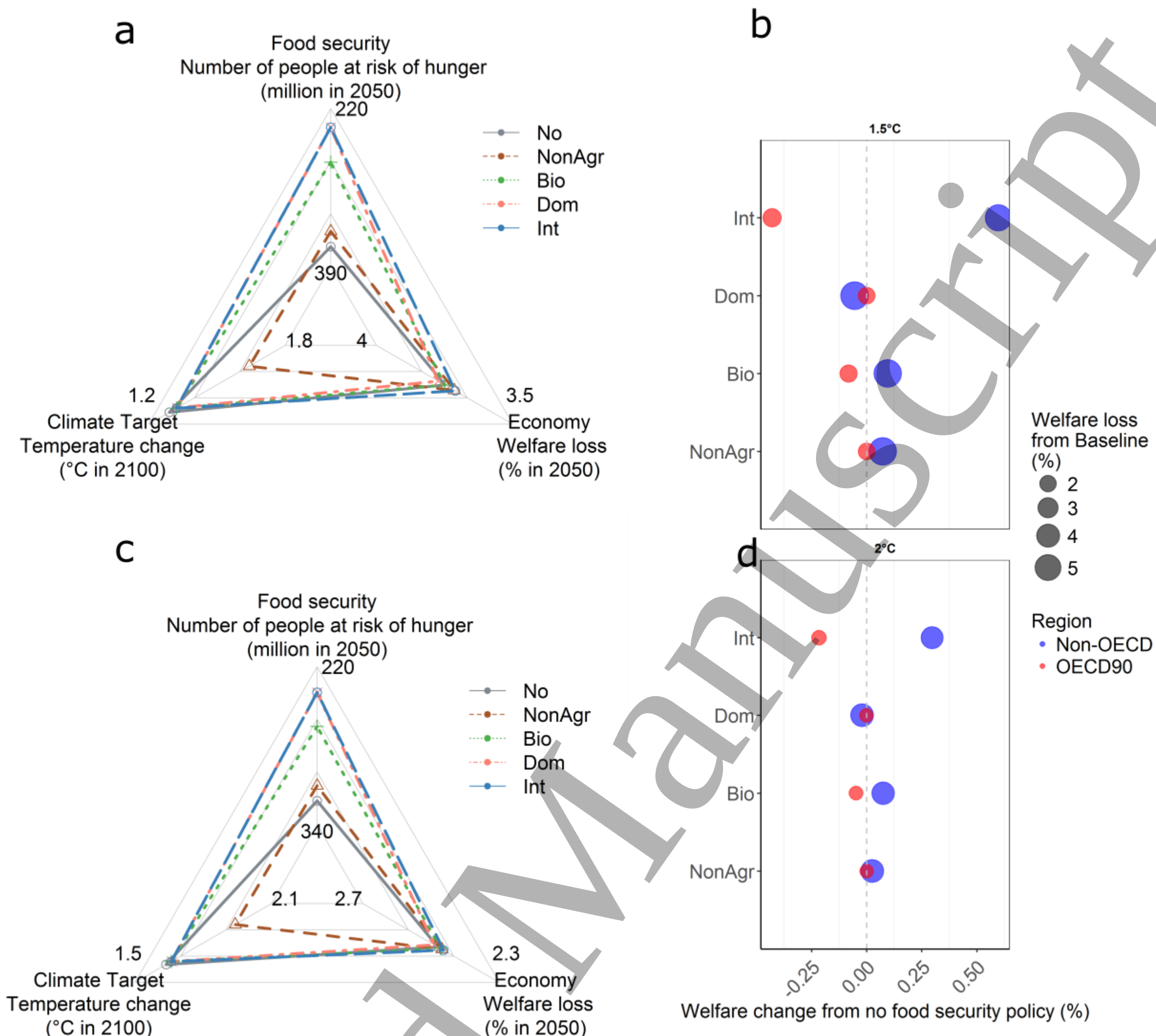

Fig. 3 | Food security, climate, and economic consequence in inclusive policy designs in SSP2 under 2°C, and 1.5°C scenarios in 2050. a and **c** depict food security, climate and economy triangles for 1.5°C and 2°C scenarios respectively. Metrics are the number of people at risk of hunger in 2050, temperature change in 2100 compared to preindustrial levels and welfare loss relative to the baseline. The food policy scenarios (1) international aid, (2) domestic reallocation, (3) a bioenergy tax, and (4) exempting agricultural non-CO_2 emissions from being priced with a carbon tax, are named "Int", "Dom", "Bio" and "NonAgr" respectively. Panel **b** and **d** illustrate macro-economic distribution changes between OECD and non-OECD regions for 1.5°C and 2°C scenarios respectively. Welfare change relative to no food security policy is shown on the x-axis, and the bubble sizes indicate the welfare loss comparing with baseline level. Data is shown for various policy packages: No, NonAgr, Bio, Dom, and Int, which represent the policy cases without, in absence of pricing of agricultural non-CO_2 emissions, with domestic allocation, and with international aid, respectively.

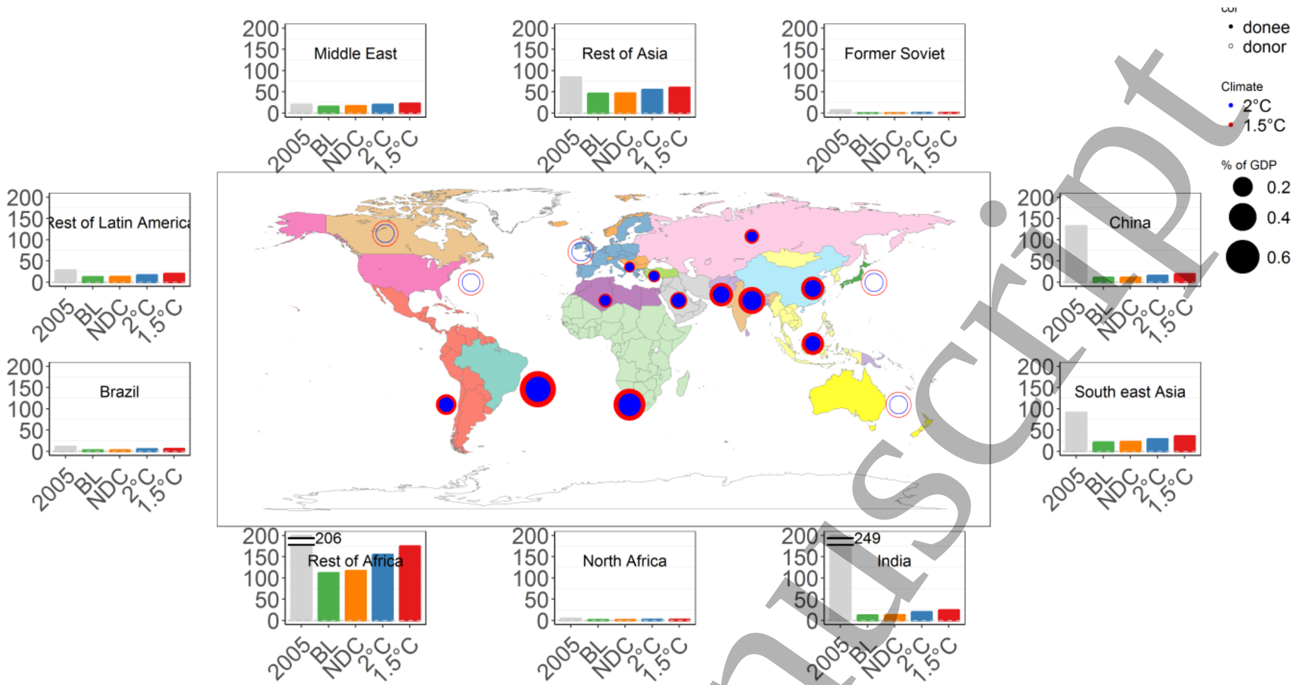

Fig. 4 | Regional distribution of the number of population at risk of hunger in SSP2 and the year 2050 and base year, and financial flows in the international aid policy case for securing food consumption. Regional number of population at risk of hunger across scenarios in units of million people. BL represents the baseline scenario. NDC, 2°C, and 1.5°C are the respective mitigation scenarios without additional food security policies. The circles indicate a financial requirement to fulfill the gap of food consumption decrease caused by exclusive climate policy shown as a percentage of GDP. The empty and filled circles indicate funders and receivers of money, respectively. Here, the international aid policy cases associated with a 2°C and 1.5°C mitigation goal is shown as a representative of food security policies.

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