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Consequence of Climate Mitigation on the Risk of Hunger

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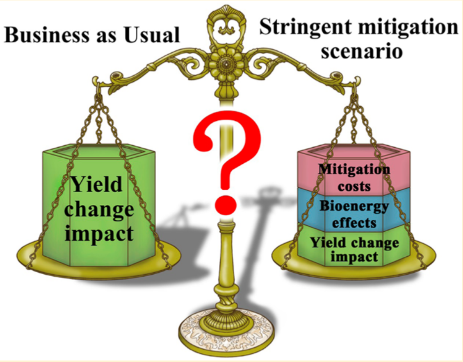
Supporting Information

ABSTRACT: Climate change and mitigation measures have three major impacts on food consumption and the risk of hunger: (1) changes in crop yields caused by climate change; (2) competition for land between food crops and energy crops driven by the use of bioenergy; and (3) costs associated with mitigation measures taken to meet an emissions reduction target that keeps the global average temperature increase to 2 °C. In this study, we combined a global computable general equilibrium model and a crop model (M-GAEZ), and we quantified the three impacts on risk of hunger through 2050 based on the uncertainty range associated with 12 climate models and one economic and demographic scenario. The strong mitigation measures aimed at attaining the 2 °C target reduce the negative effects of climate change on yields but have large negative impacts on the risk of hunger due to mitigation costs in the low-income countries. We also found that in a strongly carbon-constrained world, the change in food consumption resulting from mitigation measures depends more strongly on the change in incomes than the change in food prices.



INTRODUCTION

In general, climate change affects agricultural productivity negatively,[1] resulting in reduced food availability and increased risk of hunger. However, economic responses by both producers and consumers could alleviate some of this risk. Although mitigating greenhouse gases (GHGs) would reduce some of the negative productivity effects, mitigation may result in other effects that could increase the risk of hunger.

There are two key elements in understanding the consequences of climate mitigation. First, the use of bioenergy as a mitigation measure would increase bioenergy demand and thus also crop prices.[2] Heavy use of bioenergy would cause competition between food and energy crops due to limited land and water resources,[2−7] and it would therefore increase land and crop prices. Second, there are costs associated with mitigation, which requires changes in technologies to achieve an emissions target. Under a strong emission reduction scenario, for example, aimed at maintaining the increase in mean global temperature at no more than 2 °C, drastic mitigation measures will require high mitigation costs, including additional capital cost for energy technologies that allow a shift to a low-emission industrial structure, which, in turn, will lead to gross domestic product (GDP) losses and decreased wages and household incomes. An example of a relative cost-changing technology is the introduction of carbon capture and storage.[8] Adoption of this mitigation measure raises the cost of electricity generation that relies on fossil fuels and the products that rely on electricity. This, in turn, lowers real income and causes consumers to switch to products that are less intensive in electricity use.

The increased use of bioenergy and higher mitigation costs to lower GHG emissions both have effects on caloric intake and therefore the risk of hunger, in the first case via relative price effects and in the second case via real income effects. Although many studies have focused on impacts on the risk of hunger caused by climate change and high bioenergy demand,[6,7,9−11] no studies have discussed the impacts of mitigation costs on the risk of hunger. In addition, none of the analyses of the effects of bioenergy use were based on consistent sets of GHG concentration pathways and climate conditions used to combine the effects of climate change and of land competition, even though these effects are related to each other.

In this study, we used a suite of models that can assess both the direct biophysical effects of climate change and the indirect effects of climate mitigation measures. The main aims of this study were to evaluate (1) how large the impact on the risk of hunger due to climate mitigation would be in a stringent mitigation scenario as compared to the impact of changes in crop yields without mitigation and (2) the economic factors of

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the impact of climate mitigation measures. We focused on three major impacts on the risk of hunger: (1) crop yield changes caused by climate change; (2) land competition between food and bioenergy crops (hereafter "land competition"); and (3) mitigation costs associated with meeting an emission target (see "The AIM/CGE Model" section for detailed mitigation mechanisms). We compared the impacts of two scenarios: a stringent mitigation scenario and a business as usual (BaU) scenario. Under the stringent mitigation scenario, all three impacts can occur because of the strong emission constraint, although the negative crop yield effects of climate change might be smaller than those in the BaU scenario. In contrast, only the impact of crop yield can occur in the BaU scenario, because there are no emission constraints. This study is unique in that our analysis is based on consistent sets of GHG concentration pathways and climate conditions.

■ METHODS

Modeling Framework. The framework of the scenario analysis used in this study is shown in Figure 1. We combined the M-GAEZ process-based crop model[12] and the AIM/CGE global economic model.[13] We used a two-step modeling approach to provide some bounds on the impacts of climate change and the mitigation measures on the risk of hunger. First, an ensemble of general circulation models (GCMs) driven by different concentration pathways was combined with the M-GAEZ to understand the effects of climate change on crop yields. Second, those changes in crop yields were combined with a future socioeconomic scenario in a computable general equilibrium (CGE) model to understand consequent changes in food consumption and hunger incidence. By using this framework, we were able to take into account changes in crop yields caused by future climate change, as well as macroeconomic changes and changes in food consumption caused by mitigation measures. Yield changes due to climate change and emission pathways are exogenous variables added to the AIM/CGE model, whereas producer responses to changing land allocation and resultant land competition, mitigation costs, and income decreases are determined by the model based on the exogenous policies to reduce emissions.

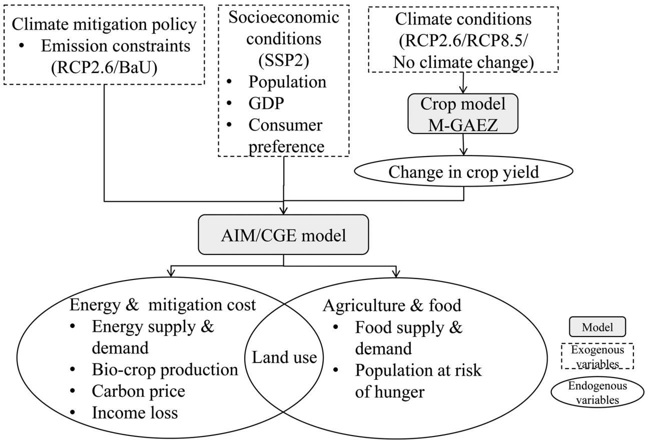

Figure 1. Modeling framework and data input and output.

The M-GAEZ Model. The M-GAEZ model[12] was developed based on the Global Agro-ecological Zones (GAEZ) model.[14] The M-GAEZ model calculates crop yield based on climate and biological conditions. The model accounts for a wide range of crop varieties with different parameters for crop growth, such as growing period and suitable climate conditions. Crop yield was estimated for each decade based on 10-year mean monthly data of the climate conditions both for the baseline and future periods. Four factors influence climate change impacts: adaptation measures, CO_2 fertilization, multicropping, and irrigation.

First, we considered two specific autonomous adaptation measures[15] under all scenarios in this study: change in crop variety and planting date.[16] Crop yields were calculated with all the varieties incorporated in the M-GAEZ model for each crop (8 for rice, 16 for wheat, 19 for maize, 6 for soybean, 3 for ground nuts, 1 for sugar cane, 5 for sugar beet, 4 for white potato, and 1 for cassava) and all the planting dates under current or future climate conditions. Then the crop variety and the planting date providing the highest yield under the conditions were selected. (See section S1 of the Supporting Information (SI) for the adaptation assumptions and validation for the baseline period.)

Second, CO_2 fertilization was included in all scenarios. Although its effect is not a focus of this study, previous studies indicated that CO_2 fertilization will influence crop yield, but the strength of this effect remains to be clarified.[12,17] To account for CO_2 fertilization, we simply multiplied parameters that change in accordance with atmospheric CO_2 concentration based on existing research.[12,18]

Third, the area of multicropping (i.e., a single crop is cultivated more than once per year on a field) can be changed in the M-GAEZ model, whereas the area of multicropping is simply fixed at the current level in the AIM/CGE model to avoid duplicate consideration. In the M-GAEZ model, if multicropping generates higher yield than single-cropping under a given climate condition at a grid cell, then the yield of multicropping is considered to be the yield of the grid cell. Namely, the future crop yields implicitly include the effect of change in suitable area for multicropping due to climate change. Additional water requirements for multicropping were considered in the decision process by calculating crop yields under precipitation and irrigation conditions.

Finally, the area of irrigation was fixed at the current level in the M-GAEZ and AIM/CGE models. That is, we assumed that the current irrigation area contains enough water for irrigation for the future. We assumed that the current degree of inconsistency is acceptable for this study, because the effect of irrigation expansion on future crop yields is limited during the study period and is not expected to affect the risk of hunger strongly. For rice, the largest irrigated crop in the world, the ratio of irrigated area to total harvested area is expected to increase gradually (from 70% to 80% between 2000 and 2050[9]).

The AIM/CGE Model. The global AIM/CGE model has been widely used for the assessment of climate change impacts and mitigation.[1,11,19−23] In the model, supply, demand, investment, and trade are described by individual behavioral functions that respond to changes in the prices of production factors and commodities, as well as changes in technology and preference parameters on the basis of assumed population, GDP, and consumer preferences.

In this study, we focused on the endogenous responses of the model. Conceptually, the given population and income growth shift the demand curve rightward, thus increasing food demand and raising prices. Producers respond to the higher price by increasing production through expanding crop cultivated area and pasture and increasing land productivity (production per unit land area) under the given land productivity and land area. Consumers respond to the price increase by decreasing consumption and shifting to less expensive goods. Some people might face the risk of hunger if they consume insufficient amounts of food. International trade globally reallocates production and consumption, decreasing food prices and contributing to a lower risk of hunger. In the same way, the given changes in crop yields due to climate change shift the supply curve leftward, thus decreasing food supply, raising prices, and resulting in the same responses to the price increase.

Production functions are formulated as multinested constant elasticity substitution (CES) functions. Household demand is formulated as a linear expenditure system function (not minimizing the risk of hunger). For trade, substitution between domestic and imported commodities is based on the Armington assumption, and the CES function is used for the aggregation of domestic and imported commodities. Disaggregation between exports and domestic supply is described by a constant elasticity transformation function. A single international trade market is assumed for each traded commodity. The model incorporates the following five mechanisms for GHG emission reductions: (1) substitution of energy with capital, caused by increased energy costs due to carbon prices; (2) bioenergy production; (3) power production by wind, solar, and geothermal energy; (4) use of carbon capture and storage technology; and (5) measures to abate GHG emissions from nonenergy sources. Possible feedstocks for ligno-cellulosic bioenergy would include not only crop residues but also purpose-grown grasses (e.g., miscanthus, switchgrass). Allocation of land by sector is formulated as a multinominal logit function[24] to reflect differences in substitutability across land categories with land rent.

The implementation of mitigation measures is represented by changing a carbon price path in the model. Once the emission constraint is implemented, the carbon price becomes a complementary variable which constrains and determines marginal mitigation cost. The carbon price raises the price of fossil fuel goods and promotes energy savings and substitution away from fossil fuels to lower emission energies. Shares of bioenergy and nonbioenergy are determined by carbon prices using a logit function. The carbon price also acts as an incentive to reduce nonenergy related emissions using a marginal abatement cost curve. Households are assumed to receive the revenue from the carbon price. The AIM/CGE model covers the full economy and captures these general response options. The model contains 17 regions and countries and 42 sectors, including 10 agricultural ones (Tables S1 and S2). (See section S2 of the SI for more details on the AIM/CGE model and parameter settings.)

The population at risk of hunger is calculated outside the AIM/CGE model by using the FAO approach.[25] Amounts of food consumption vary among households within a country, and people who eat less than the minimum energy requirement face the risk of hunger. The AIM/CGE model calculates mean per-capita food consumption for a representative household. The proportion of the population at risk of hunger is estimated from the mean per-capita food consumption, the minimum energy requirement, and the coefficient of variation of distribution of dietary energy consumption among households within each country.[25] Future changes in inequality of food distribution in a country are considered by changing the coefficient of variation along with income growth. We assumed no risk of hunger for high-income countries. (See section S3 of the SI for more details on the methods used to estimate the risk of hunger.)

Crop Yields under the BaU and Mitigation Scenarios. Crop yields in the no climate change (NoCC) case, in which climate conditions remain at current levels, were input to the AIM/CGE model to reflect a wide range of technology developments, such as increasing fertilizer input, improving crop varieties, and expanding irrigation.[26] However, these yields do not reflect the impacts of climate change. To calculate those impacts, the changes in crop yield due to climate change are input to the AIM/CGE model as a change ratio from the NoCC level. We used the assumption of the Agriculture Model Intercomparison and Improvement Project (AgMIP)[22] as the crop yield in the NoCC case (Table S5). For scenarios with climate change, we calculated the yield change of rice, wheat, maize, soybean, ground nuts, sugar cane, sugar beet, white potato, and cassava by using M-GAEZ. We used the yield change of maize for grains other than rice and wheat, the weighted average of yield changes of soybean and ground nuts for oil crops, those of sugar beet and sugar cane for sugar crops, and those of white potato and cassava for "other crops" (Table S6). To input the grid-based yield information into the AIM/CGE model, the gridded yields were weighted by the present cropland area and spatially aggregated into regional values. To clarify the uncertainty range associated with different climate models, we used results from the 12 climate models contributing to the fifth phase of the Climate Model Intercomparison Project (CMIP5; Table S6).

Socioeconomic Scenarios and Data. For population and GDP we used the shared socioeconomic pathways (SSPs),[27] which are being developed internationally to perform cross-sectoral assessments of climate change impact, adaptation, and mitigation. The SSPs consist of five future scenarios, including both qualitative and quantitative information in terms of challenges in mitigation and adaptation to climate change. This study uses SSP2 describing a "middle of the road" scenario (Figure S9). In this study we focus on the new perspective of evaluating the global situation based on RCP2.6 and impacts of mitigation measures and would like to address the uncertainty of socioeconomic conditions as a further step. We assumed the two above-mentioned specific autonomous adaptation measures of change in crop variety and planting date. This means that even in low-income countries, economic development will proceed, appropriate technologies will be disseminated, and the possibility of their use will increase. Implementation of these adaptation measures requires appropriate farming techniques and long-term weather forecasts.

As future climate conditions in the M-GAEZ and GHG emission constraints in the AIM/CGE model, we used two representative concentration pathways (RCPs): RCP2.6[28] and RCP8.5.[29] RCPs have been developed[30] and widely used in research on climate change in recent years. RCP2.6 and RCP8.5 are the GHG concentration pathways corresponding to the radiative forcing reaching at level of approximately 2.6 and 8.5 W/m^2, respectively, by the end of the 21st century.[28,29] In RCP2.6, a global mean temperature rise from preindustrial times likely stays below 2 °C.[31] In contrast, RCP8.5 incorporates the highest level of climate change (Figure S8).

Impact Assessment Approach Used in This Study. Our study quantified the impacts on food consumption caused by changes in crop yields, land competition, and mitigation costs by comparing multiple scenarios, as shown in Table 1. The

Table 1. Scenarios in This Study[a]

scenario	abbrev	climate conditions	climate mitigation policy	other assumptions	impacts analyzed
reference	S0	NoCC	no policy		
mitigation	S1	RCP2.6	RCP2.6		C1+B+E
BaU	S2	RCP8.5	no policy		C2
subscenario					
	S1-C1	RCP2.6	no policy		C1
	S1-BE	NoCC	RCP2.6		B+E
	S1-E	NoCC	RCP2.6	no land competition between food and energy crops	E

[a] NoCC: no climate change, assuming present climate conditions for the future. No policy: no emission constraints and mitigation policy. C1: climate change impact according to a 2 °C increase by the end of the 21st century. C2: climate change impact according to a 4 °C increase. B: bioenergy impact through land competition between food crops and bioenergy corps. E: mitigation costs impact.

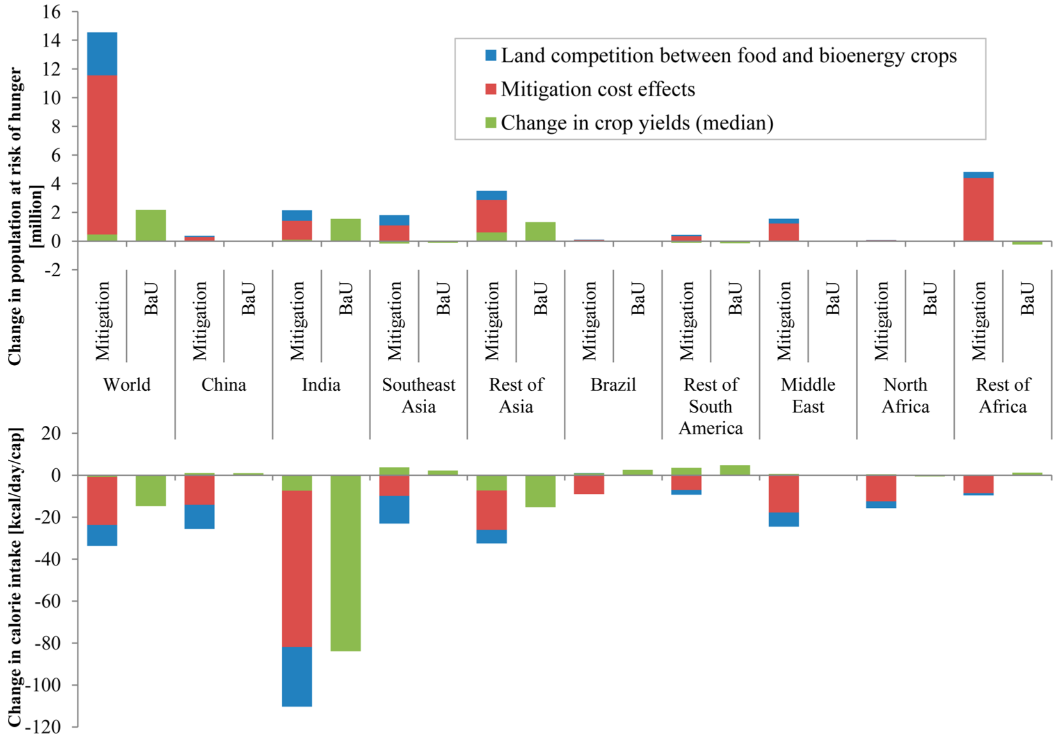

Figure 2. Change in the population at risk of hunger (top) and caloric intake (bottom) in the world and selected countries under the stringent mitigation scenario (S1) and the BaU scenario (S2) in 2050 caused by the three factors from the reference level (S0) with no climate change. These impacts of change in crop yields (green bars) represent median values among the 12 GCMs. Under no climate change (S0), the world population at risk of hunger was 90 million, and global mean food consumption was 2950 kcal/day/person in 2050. See Figures S18 and S19 for regional caloric intake and risk of hunger at S0.

scenarios have different assumptions for three variables: (1) change in crop yields caused by climate change; (2) global GHG emission constraints for climate stabilization; and (3) land use (i.e., whether land is used for bioenergy crop production). The reference scenario (S0) assumes current climate conditions (NoCC) and does not assume climate mitigation policy, such that no emission target is set (i.e., no emission constraints). The mitigation scenario (S1) sets climate conditions and mitigation policy to RCP2.6, whereas the BaU scenario (S2) assumes climate conditions of RCP8.5 and no mitigation policy. We assumed RCP8.5 for S2 because GHG emissions from the AIM/CGE model are similar to those of RCP8.5.[29]

Three subscenarios, S1-C1, S1-BE, and S1-E, were developed to estimate the impact of each factor under climate mitigation by calculating the differences among them. The symbols indicate three factors under climate mitigation respectively: crop yield change due to climate change according to the 2 °C target (C1), impacts caused by bioenergy through land competition between food and bioenergy crops (B), and mitigation costs due to climate mitigation (E). S1-C1 has climate conditions of RCP2.6 and no mitigation policy. S1-BE assumes NoCC and sets the mitigation policy to RCP2.6. We assumed the crop yields under present climate conditions (NoCC) for the future and limited GHG emissions at the RCP2.6 level. We analyzed this hypothetical scenario S1-BE to assess the impacts of climate mitigation. S1-E not only has the same conditions as S1-BE but also assumes that land is not needed for bioenergy crop production in order to quantify the impact of bioenergy production through land competition between bioenergy and food crops. This is based on the idea that if land is not needed for bioenergy crop production, there will be no land competition between food and bioenergy crops. Accordingly, S1-E calculations use a production function that assumes that no land is used for bioenergy production. This analysis covers the years 2005−2050.

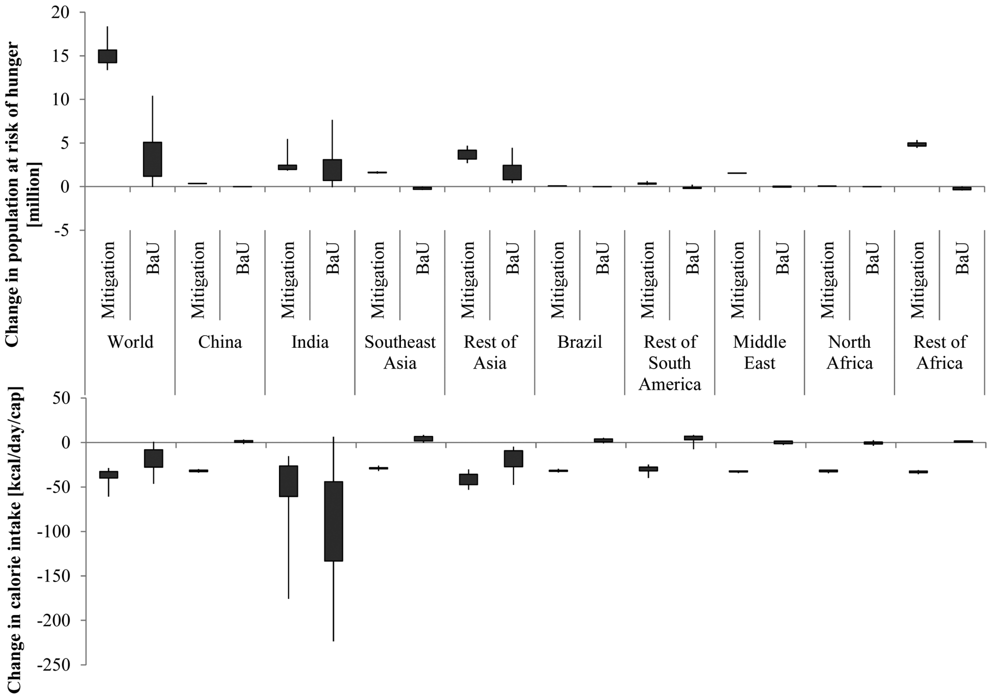

Figure 3. Change in the population at risk of hunger (top) and caloric intake (bottom) in the world and selected countries under the stringent mitigation scenario (S1) and the BaU scenario (S2) in 2050 caused by the three factors from the reference level (S0) with no climate change. Boxes represent the first to third quartile range across the 12 GCMs, and the vertical lines extend to the most extreme data points. Under no climate change (S0), the world population at risk of hunger was 90 million, and global mean food consumption was 2950 kcal/day/person in 2050. See Figures S18 and S19 for regional caloric intake and risk of hunger at S0.

The following procedure was used to calculate impacts from the three factors using subscenarios of S1. First, we calculated the combined impact of the three factors [B+E+C1] as the difference between S1 and S0. Next, we calculated the impact of climate change [C1] as the difference between S1-C1 and S0 and then calculated the impact of land competition and mitigation cost [B+E] as the difference between S1-BE and S0. To distinguish between [B] and [E], we calculated the impact due to land competition [B] as the difference between S1-E and S1-BE, and used as [E] the remainder after subtracting [B] from [B+E]. Up to this point, we estimated the impact of each factor by calculating the differences among scenarios, but because the AIM/CGE model contains various factors that influence each other, S1 results might include several effects. We checked the magnitude of this crossover effect and found that globally it was 2.3 kcal/day/person and regionally 17 kcal/day/person at maximum. Therefore, this estimation method appears to be valid (see section S4 of the SI).

■ RESULTS

Impacts on Food Consumption and Population at Risk of Hunger. Globally, the total impact of changes in crop yields, land competition, and mitigation costs in the stringent mitigation scenario (S1) was much greater than the impact of yield change alone in the BaU scenario (S2). Figure 2 compares the world and regional impacts on food consumption and risk of hunger in 2050 between the mitigation (S1) and BaU (S2) scenarios relative to the reference scenario (S0) with no climate change (see Figure S20 for all countries and Table S8 for actual changes in crop production by regions). The impact of mitigation costs is predicted to be the largest among the three factors: it will decrease global mean food consumption by 23 kcal/day/person and increase the global population at risk of hunger by 11 million (12%) from the S0 level.

The impact on food associated with land competition in mitigation scenario (S1) is estimated to be comparable to the impact of crop yield change in the BaU scenario (S2). The impact of land competition depends especially on the combination of the increases in bioenergy demand, land prices, and crop producer prices caused by limited land availability. Therefore, the impact is limited to a few countries which have the bioenergy demand increase and limited land availability, and the regional distribution of the impact is not necessarily the same as that of bioenergy production (see Figure S21 for regional bioenergy production and Figure S22 for comparison with other studies). For China, one of the bioenergy-producing countries, the impact of land competition is small because it is expected to be reduced as a result of population decline and yield increases, which, in turn, will decrease cropland area.

In all the examined regions, food consumption in the stringent mitigation scenario (S1) is estimated to be lower than in the BaU scenario (S2). For example, in India, the total impact of the three factors on food consumption under strong mitigation will be very large and comparable to the impact due to yield change in BaU. There are several reasons for this. First, the large macroeconomic impact is caused by a large change in income through high elasticity to income change. Second, in India, wheat and "other crops" (Table S3) are consumed in large amounts, the impacts on the yields of the two crop categories are large, and land suitable for agriculture and for cropland expansion is limited. Third, under the stringent mitigation scenario, future bioenergy demand will be high. Thus, even a small increase in bioenergy production is expected to cause further land competition and affect food consumption. Fourth, a further increase in food imports is limited. Food trade

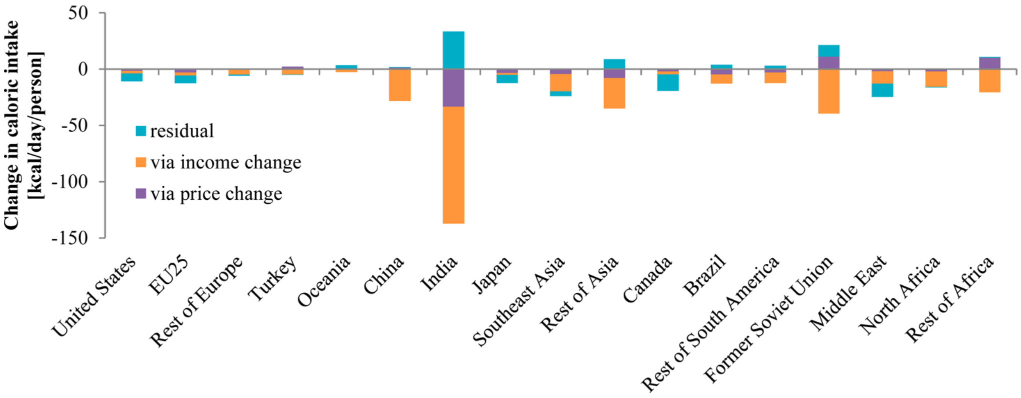

Figure 4. Change in caloric intake via several processes in 2050 caused by implementation of mitigation measures (S1-BE) from the reference level (S0) with no climate change. Residual describes change in caloric intake via other processes, such as cross-price effects.

is based on the Armington assumption and the CES function. When a share parameter of the function is small, the absolute amounts of domestic and imported commodities are unable to change drastically in response to a price change, whereas a share of the two commodities is able to change drastically. This is discussed in more detail in the "Limitations and Future Developments" section.

The regional distribution of impacts on the population at risk of hunger is different from that on food consumption because the population at risk of hunger with no climate change (S0) and degree of impact on food consumption differ among regions. The impact on the population at risk of hunger is large in the rest of Africa (including Sub-Saharan Africa and excluding North Africa) and the rest of Asia (excluding Japan, China, India, and Southeast Asia) because large populations will face a risk of hunger under S0 (Figure S19).

Figure 3 shows the total impacts of changes in crop yields, land competition, and mitigation costs on food consumption and the population at risk of hunger in 2050 for the stringent mitigation scenario (S1) and BaU (S2), along with the uncertainty range among all 12 GCMs (see Figure S23 for all countries). Even when considering the uncertainty range of multiple GCMs, the impacts of mitigation measures under S1 is comparable to impacts of yield changes under S2. For particular regions, the uncertainty range depends on uncertainty of yield changes and degree of crop consumption. For example, the uncertainty range of India is large because of large uncertainty of yield changes of wheat and "other crops" (Table S3), which are consumed in large amounts in India. (See section S7 in the SI for regional yield changes due to climate change with uncertainty ranges across GCMs.)

We compared our estimated climate impacts on food consumption under RCP8.5 with the AgMIP modeling comparisons.[32] Both studies showed significant impacts but with different ranges. The ranges vary depending on the models considered. The AgMIP's range (−167 to −1.6 kcal/day/person) was wider because of the number of economic models considered, but it overlapped somewhat with this study's range (−46 to +0.95 kcal/day/person) (Figure S24). See section S8 of the SI for comparisons of yield changes due to climate change with the AgMIP study.

Decomposition Analysis of Processes by Which Mitigation Measures Change Caloric Intake. In general, changes in crop yields, land competition, and mitigation costs affect food consumption via two processes: (1) these factors further increase food prices, in turn decreasing food demand through price elasticity, and (2) they reduce income, in turn reducing food demand through income elasticity. To elucidate the relative contributions of these two processes, we decomposed the changes in food consumption (the equations are shown in section S5 of the Supporting Information).

Figure 4 shows change in caloric intake via several processes caused by mitigation measures under the stringent mitigation scenario (S1-BE). Implementing mitigation measures will affect medium- and low-income countries. The effects due to income changes are larger than those due to price changes. The changes in caloric intake via income changes are caused mainly by mitigation costs (Figure S26), which ultimately leads to GDP loss and decreased income. The magnitude of the mitigation cost effects on income varies across regions for several reasons. First, the degree of income effect seems to be related to the changing rate of energy prices induced by a higher carbon price than that of the BaU level. For example, for the former Soviet Union and India, energy prices are estimated to be markedly changed by the mitigation measures. Second, a share of energy expenditure to total household expenditure is high, for example, in the former Soviet Union. The residuals in Figure 4 describe changes in caloric intake via other processes, including cross-price effects, that were not included in the above price effects. See section S5 of the SI for the residuals for more detail.

■ DISCUSSION

Impact on Food Consumption. In this study, we quantified the impacts on food consumption and the population at risk of hunger that would result from three factors related to climate change and mitigation measures under consistent sets of GHG emission pathways and climate conditions. Our analyses revealed two major findings. First, the impact on the risk of hunger due to land competition and mitigation costs under the stringent mitigation scenario would be much larger than those due to changes in crop yields under the BaU scenario. Second, the change in food consumption caused by mitigation measures depends more strongly on income changes than price changes.

To our knowledge, this study is the first to quantify the impacts of land competition and mitigation costs. Compared with the impact of yield change, the degree of these impacts is substantial and certainly should be considered in future research and policy decisions. Our results suggest that if carbon taxes are imposed uniformly worldwide across regions and countries, implementing mitigation measures will affect

Africa and Asia regions because of large populations at risk of hunger at no climate change level. Thus, if carbon taxes are levied uniformly worldwide, other measures that alleviate the impacts of mitigation measures on these countries would become necessary, such as providing food aid.

While climate mitigation measures diminish the diverse negative impacts of climate change, this study considered only the moderation of crop yield decline. In addition, among the many different problems caused by climate change, including its negative effects on ecosystems, water resources, food, and health, this study addressed only the impacts on the risk of hunger. Therefore, although some people may interpret our results to indicate that it would be better not to implement climate mitigation measures in view of these results, we do not agree with that perspective. Again, the objective of this study was simply to determine the impacts of mitigation measures on food consumption and the population at risk of hunger.

Limitations and Future Developments. Here we discuss some of the limitations of the framework and methods used in this study.

- RCP2.6 or equivalent emission targets are very challenging to achieve. Our results are based on implementing a particular set of assumed measures for reaching RCP2.6, but there are many alternative pathways to this target. Recent studies aimed at stabilizing atmospheric GHG concentrations at low levels have discussed technology costs and availability, how actions should be scheduled, associated macroeconomic costs, and participation of developing regions. Research presented at the Energy Modeling Forum 27, which is one of the most well-known modeling intercomparison projects in the integrated assessment modeling community, explored the implications of technology costs and availability for the feasibility and macroeconomic costs of energy system transformations to achieve climate stabilization. For example, Kriegler et al.[8] found that the unavailability of carbon capture and storage and limited availability of bioenergy have the largest impact on feasibility and macroeconomic costs for reaching stable low GHG concentrations. In addition, the AMPERE modeling comparison project focused on the implications of near-term policies for the costs and attainability of long-term climate objectives. Riahi et al.[33] showed that a 2030 mitigation effort comparable to the international pledges would result in a further "lock-in" of the energy system into fossil fuels and thus impede the required energy transformation to reach stable low GHG concentrations (equivalent to RCP2.6). Our study did not take into account constraints such as unavailability and timing of technology implementations for any regions and sectors. Because such constraints might change our results, further research is warranted.
- We focused only on gradual changes of climate conditions, as the first step. Further research needs to focus on extreme events (i.e., drought, flooding, heat waves) and climate variability, which are particularly important in terms of the risk of hunger.
- This study aggregated the world into 17 regions to provide an overview of the impacts on the risk of hunger. Because the magnitude of the effects of climate change has a spatial distribution, a regional downscaling could help clarify the spatial distribution of the impacts and provide more useful information.
- Current land-use regulations for bioenergy crop production were not considered. Bioenergy production on land for food production was allowed in our analyses, even though the Indian government has explicitly ruled out bioenergy feedstock production on land suitable for food production. We made the simplifying assumption that current land regulations would not be maintained under the strong climate mitigation measures required to meet RCP2.6. However, even if we assumed the current Indian land-use regulation for the future in our analysis, which would decrease the land competition factor, our main findings would not change largely because the macroeconomic impact due to GDP loss in India would still be large.
- Future crop yields might change in response not only to crop prices but also labor and capital prices and fertilizer costs which in current model crop yields do not change by responding to. Moreover, the degree of technology development currently considered in the exogenous yields might change in response to crop prices. It may be the case that crop yields should be calculated by using other detailed technology models, which will require more research.
- The decrease in labor population and productivity caused by impacts on food consumption were not fed back into the recursive calculation. However, we assumed that labor population and productivity would not strongly influence the current results.
- We considered only two specific autonomous adaptations for agricultural production (i.e., change in crop variety and planting date) and not the costs of these adaptations or other adaptations such as irrigation expansion. This likely resulted in underestimation of the economic impacts of these adaptation measures. Further studies that incorporate adaptation costs and other adaptations are needed.
- This study used the single socioeconomic condition of SSP2, a single economic model, and a study period ending in 2050. These limitations could be addressed by using multiple socioeconomic conditions and economic models. As shown by the AgMIP,[1] different degrees of price elasticity of land-use change among models might lead to different results. In addition, extending the time period to 2100 would enable us to clarify the predicted situation in the second half of this century.
- Food trade is one of the key issues in this study because the impacts on the risk of hunger can be alleviated by food trade. Although the CES function with the Armington assumption has the advantage of differentiating domestic and imported commodities, it does not allow drastic change in the absolute amounts of the two commodities when a share parameter of the function is small. Another description of trade in economic models can be net trade, which simply considers the gap between domestic production and consumption. Although the net-trade approach would allow for a drastic change in trade, taxes and tariffs are not considered, and there is no economic theory behind the function and no reproducible parameters for this. Various trade functions have different merits and disadvantages. Further research is necessary to investigate whether the CES function is truly appropriate for this analysis.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional text, Figures S1–S28, and Tables S1–S8. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/es5051748.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Nelson, G. C.; Valin, H.; Sands, R. D.; Havlík, P.; Ahammad, H.; Deryng, D.; Elliott, J.; Fujimori, S.; Hasegawa, T.; Heyhoe, E.; Kyle, P.; Von Lampe, M.; Lotze-Campen, H.; Mason d'Croz, D.; van Meijl, H.; van der Mensbrugghe, D.; Müller, C.; Popp, A.; Robertson, R.; Robinson, S.; Schmid, E.; Schmitz, C.; Tabeau, A.; Willenbockel, D. Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111* (9), 3274−3279.

(2) Lotze-Campen, H.; von Lampe, M.; Kyle, P.; Fujimori, S.; Havlik, P.; van Meijl, H.; Hasegawa, T.; Popp, A.; Schmitz, C.; Tabeau, A.; Valin, H.; Willenbockel, D.; Wise, M. Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agric. Econ.* **2014**, *45* (1), 103−116.

(3) Smith, P.; Gregory, P. J.; van Vuuren, D.; Obersteiner, M.; Havlik, P.; Rounsevell, M.; Woods, J.; Stehfest, E.; Bellarby, J. Competition for land. *Philos. Trans. R. Soc. London, Ser. B* **2010**, *365* (1554), 2941−57.

(4) Valentine, J.; Clifton-Brown, J.; Hastings, A.; Robson, P.; Allison, G.; Smith, P. Food vs. fuel: the use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production. *GCB Bioenergy* **2012**, *4* (1), 1−19.

(5) Fisher, B.; Nakicenovic, N.; Alfsen, K.; Corfee Morlot, J.; de la Chesnaye, F.; Hourcade, J.-C.; Jiang, K.; Kainuma, M.; La Rovere, E.; Matysek, A.; Rana, A.; Riahi, K.; Richels, R.; Rose, S.; van Vuuren, D.; Warren, R. *Issues related to mitigation in the long term context*; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2007.

(6) Msangi, S.; Ewing, M.; Rosegrant, M. W.; Zhu, T. *Biofuels, Food Security, and the Environment: A 2020/2050 Perspective* **2010**, 65−94.

(7) Fischer, G. *How can climate change and the development of bioenergy alter the long-term outlook for food and agriculture*; FAO: Rome, Italy, 2011; pp 95−155.

(8) Kriegler, E.; Weyant, J.; Blanford, G.; Krey, V.; Clarke, L.; Edmonds, J.; Fawcett, A.; Luderer, G.; Riahi, K.; Richels, R.; Rose, S.; Tavoni, M.; van Vuuren, D. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change* **2014**, *123* (3−4), 353−367.

(9) Nelson, G. C., Rosegrant, M. W.; Amanda, P.; Gray, I.; Ingersoll, C.; Robertson, R.; Tokgoz, S.; Zhu, T.; Sulser, T. B.; Ringler, C.; Msangi, S.; You, L. *Food security, farming, and climate change to 2050, Scenarios, results, policy options*; IFPRI: Washington, DC, USA, 2010.

(10) Parry, M.; Rosenzweig, C.; Livermore, M. Climate change, global food supply and risk of hunger. *Philos. Trans. R. Soc. London, Ser. B* **2005**, *360* (1463), 2125−38.

(11) Hasegawa, T.; Fujimori, S.; Shin, Y.; Takahashi, K.; Masui, T.; Tanaka, A. Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. *Environ. Sci. Technol.* **2014**, *48* (1), 438−445.

(12) Masutomi, Y.; Takahashi, K.; Harasawa, H.; Matsuoka, Y. Impact assessment of climate change on rice production in Asia in comprehensive consideration of process/parameter uncertainty in general circulation models. *Agric., Ecosyst. Environ.* **2009**, *131* (3−4), 281−291.

(13) Fujimori, S.; Masui, T.; Matsuoka, Y. *AIM/CGE [basic] manual*; Center for Social and Environmental Systems Research, NIES: Tsukuba, Japan, 2012.

(14) Fischer, G.; Shah, M.; van Velthuizen, H.; Nachtergaele, F. O. *Global agro-ecological assessment for agriculture in the 21st century*; IIASA: 2002.

(15) Easterling, W. E.; Aggarwal, P. K.; Batima, P.; Brander, K. M.; Erda, L.; Howden, S. M.; Kirilenko, A.; Morton, J.; Soussana, J.-F.; Schmidhuber, J.; Tubiello, A. F. N. *Food, fibre and forest products. Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate ChangeParry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., Hanson, C. E., Eds.; Cambridge University Press: Cambridge, UK, 2007.

(16) Fischer, G.; Shah, M.; Tubiello, F. N.; van Velhuizen, H. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990−2080. *Philos. Trans. R. Soc. London, Ser. B* **2005**, *360* (1463), 2067−83.

(17) Denman, K. L.; Brasseur, G.; Chidthaisong, A.; Ciais, P.; Cox, P. M.; Dickinson, R. E.; Hauglustaine, D.; Heinze, C.; Holland, E.; Jacob, D.; Lohmann, U.; Ramachandran, S.; Leite da Silva Dias, P.; Wofsy, S. C.; Zhang, X. *Couplings between changes in the climate system and biogeochemistry*; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2007; p Medium: ED.

(18) Tubiello, F. N.; Amthor, J. S.; Boote, K. J.; Donatelli, M.; Easterling, W.; Fischer, G.; Gifford, R. M.; Howden, M.; Reilly, J.; Rosenzweig, C. Crop response to elevated CO2 and world food supply: A comment on "Food for Thought···" by Long et al., Science 312:1918−1921, 2006. *Eur. J. Agron.* **2007**, *26* (3), 215−223.

(19) Fujimori, S.; Masui, T.; Matsuoka, Y. Development of a global computable general equilibrium model coupled with detailed energy end-use technology. *Appl. Energy* **2014**, *128* (0), 296−306.

(20) Masui, T.; Matsumoto, K.; Hijioka, Y.; Kinoshita, T.; Nozawa, T.; Ishiwatari, S.; Kato, E.; Shukla, P. R.; Yamagata, Y.; Kainuma, M. An emission pathway for stabilization at 6 Wm^{-2} radiative forcing. *Clim. Change* **2011**, *109* (1−2), 59−76.

(21) Ishida, H.; Kobayashi, S.; Kanae, S.; Hasegawa, T.; Fujimori, S.; Shin, Y.; Takahashi, K.; Masui, T.; Tanaka, A.; Honda, Y. Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. *Environ. Res. Lett.* **2014**, *9* (6), 064014.

(22) von Lampe, M.; Willenbockel, D.; Ahammad, H.; Blanc, E.; Cai, Y.; Calvin, K.; Fujimori, S.; Hasegawa, T.; Havlik, P.; Heyhoe, E.; Kyle, P.; Lotze-Campen, H.; Mason d'Croz, D.; Nelson, G. C.; Sands, R. D.; Schmitz, C.; Tabeau, A.; Valin, H.; van der Mensbrugghe, D.; van Meijl, H. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agric. Econ.* **2014**, *45* (1), 3−20.

(23) Nelson, G. C.; van der Mensbrugghe, D.; Ahammad, H.; Blanc, E.; Calvin, K.; Hasegawa, T.; Havlik, P.; Heyhoe, E.; Kyle, P.; Lotze-Campen, H.; von Lampe, M.; Mason d'Croz, D.; van Meijl, H.; Müller, C.; Reilly, J.; Robertson, R.; Sands, R. D.; Schmitz, C.; Tabeau, A.; Takahashi, K.; Valin, H.; Willenbockel, D. Agriculture and climate change in global scenarios: why don't the models agree. *Agric. Econ.* **2014**, *45* (1), 85−101.

(24) Fujimori, S.; Hasegawa, T.; Masui, T.; Takahashi, K. Land use representation in a global CGE model for long-term simulation: CET vs. logit functions. *Food Sec.* **2014**, *6* (5), 685−699.

(25) FAO *FAO Methodology for the measurement of food deprivation: updating the minimum dietary energy requirements*; FAO: Rome, 2008.

(26) Robinson, S.; van Meijl, H.; Willenbockel, D.; Valin, H.; Fujimori, S.; Masui, T.; Sands, R.; Wise, M.; Calvin, K.; Havlik, P.; Mason d'Croz, D.; Tabeau, A.; Kavallari, A.; Schmitz, C.; Dietrich, J. P.; von Lampe, M. Comparing supply-side specifications in models of global agriculture and the food system. *Agric. Econ.* **2014**, *45* (1), 21−35.

(27) IIASA, Shared Socioeconomic Pathways (SSP) Database Version 0.9.3. In 2012.

(28) Vuuren, D. P.; Stehfest, E.; Elzen, M. G. J.; Kram, T.; Vliet, J.; Deetman, S.; Isaac, M.; Klein Goldewijk, K.; Hof, A.; Mendoza Beltran, A.; Oostenrijk, R.; Ruijven, B. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Clim. Change* **2011**, *109* (1−2), 95−116.

(29) Riahi, K.; Rao, S.; Krey, V.; Cho, C.; Chirkov, V.; Fischer, G.; Kindermann, G.; Nakicenovic, N.; Rafaj, P. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Clim. Change* **2011**, *109* (1−2), 33−57.

(30) van Vuuren, D. P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G. C.; Kram, T.; Krey, V.; Lamarque, J.-F.; Masui, T.; Meinshausen, M.; Nakicenovic, N.; Smith, S. J.; Rose, S. K. The representative concentration pathways: an overview. *Clim. Change* **2011**, *109* (1−2), 5−31.

(31) UNFCCC, The Cancun Agreements. In 2011.

(32) Valin, H.; Sands, R. D.; van der Mensbrugghe, D.; Nelson, G. C.; Ahammad, H.; Blanc, E.; Bodirsky, B.; Fujimori, S.; Hasegawa, T.; Havlik, P.; Heyhoe, E.; Kyle, P.; Mason-D'Croz, D.; Paltsev, S.; Rolinski, S.; Tabeau, A.; van Meijl, H.; von Lampe, M.; Willenbockel, D. The future of food demand: understanding differences in global economic models. *Agric. Econ.* **2014**, *45* (1), 51−67.

(33) Riahi, K.; Kriegler, E.; Johnson, N.; Bertram, C.; den Elzen, M.; Eom, J.; Schaeffer, M.; Edmonds, J.; Isaac, M.; Krey, V.; Longden, T.; Luderer, G.; Méjean, A.; McCollum, D. L.; Mima, S.; Turton, H.; van Vuuren, D. P.; Wada, K.; Bosetti, V.; Capros, P.; Criqui, P.; Hamdi-Cherif, M.; Kainuma, M.; Edenhofer, O. Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* **2015**, *90*, 8−23.