Integrated Development Program Discussion Paper 1

Dietary adaptation mechanisms to the potential health impacts of climate related changes in micronutrients in wheat and other cereals

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CIMMYT
International Maize and Wheat Improvement Center

CGIAR
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and Markets
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CGIAR

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The International Maize and Wheat Improvement Center (CIMMYT) is a non-profit international agricultural research and training organization. CIMMYT focuses on sustainable agri-food systems and improved livelihoods through research on maize, wheat and other food crops.

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Declaration of interest statement

The authors declare no conflicts of interest in the publication of this research.

Purpose of the series

CIMMYT's *Integrated Development Program Discussion Paper* series publishes preliminary research results and study protocols prior to finalizing them for submission as peer-reviewed journal articles. The discussion papers are intended to solicit discussion and comments from stakeholders and peers to improve the quality of the research outputs.

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Abstract

The climate-change impacts on nutrient levels in staple grains could negatively impact mineral deficiencies amongst at-risk populations, in particular, of iron and zinc. Here we analyse potential dietary-adaptation strategies to such impacts. By pairing nutritional, dietary health and dietary-scenario analyses, we found that replacement of refined grains by whole grains could help compensate the climate-change-related reductions in iron and zinc concentrations in wheat, rice, maize, and improve dietary risks related to low wholegrain/fibre intake. A more comprehensive dietary-change strategy of adopting healthy and sustainable diets would impart further nutritional and health benefits, whilst also contributing to climate-change mitigation.

Preface

The PIM-initiated and CIMMYT-led project “Effects of dietary change on the future demand for major cereals” was a collaborative effort across the CGIAR involving researchers from CIMMYT, ICARDA, IITA, IRRI and IFPRI as well as a CRP Wheat funded contribution by Oxford University.

The objective of this project was to determine consumption pattern changes, linked to the relevant global drivers of change in some key countries. This allowed the team to explore expected changes in demand under different scenarios (urbanization, population, prices). Dietary change was analyzed according to rural-urban axis. The team used the case studies to provide well-documented examples of actual and potential dietary change.

The insights gleaned from these studies is of crucial importance for technology development for major cereals as well as providing insights into the expected pathways related to the One CGIAR impact area of nutrition and health.

Sieglinde Snapp

Director CIMMYT Integrated Development Program

1. Introduction

Climate change is expected to pose several threats to food security (IPCC), including nutrient availability. Elevated concentrations of atmospheric carbon dioxide have been found to reduce the mineral concentrations in grains (Loladze, 2014; Myers et al., 2014b). Of particular health concern are changes in micronutrients, such as iron and zinc, for which grains are the primary dietary source (Shewry and Hey, 2015), and substantial global deficiencies exist (Forouzanfar et al., 2015). Assuming no other changes would occur to baseline diets, modelling study have estimated that the number of people at risk of zinc deficiency could increase by 138 million by 2050 (Myers et al., 2015), those at risk of iron deficiency by 1.4 billion (Smith et al., 2017), and there may be additional threats to protein intake (Medek et al., 2017) and levels of B vitamins (Zhu et al., 2018).

There are several ways of adapting to the potential reductions in nutrient concentrations. From the production side, most efforts have been focused on breeding climate-resilient crop varieties that would mitigate the potential reductions in yields related to climate-change impacts, such as changes in temperature and rainfall (Cairns and Prasanna, 2018; CrespoHerrera et al., 2018; Tesfaye et al., 2018). Modelling studies have indicated that yield improvements can more than offset the adverse effects of climate change on yields (Islam et al., 2016) and on nutrient levels (Beach et al., 2019). However, a recent modelling study has also indicated that breeding climate-resilient crop varieties, e.g., of wheat, could further exacerbate nutrient deficiencies when yields are the sole focus (Asseng et al., 2019).

More nutrient-focused adaptation methods are available on the consumption side. Those include targeted supplementation or biofortification with at-risk nutrients, as well as dietary changes towards more nutritious diets. Here we focus on the latter and estimate the impacts that two dietary-change strategies could have on the potential reductions in nutrient concentration related to climate change, in particular on protein, zinc, and iron intake, as well as on other dietary-health impacts of climate change. The strategies include a targeted intervention that increases the whole-grain content of diets by replacing all refined grains with whole grains, and a more comprehensive strategy of dietary change towards healthy and sustainable diets. In addition to contributing to nutrition security, the latter would have the additional benefit of contributing to climate-change mitigation by reducing food-related greenhouse gas emissions (Springmann et al., 2018a, 2018b).

2. Methods

2.1. Nutritional analysis

We estimated the nutrient content of foods by pairing the consumption of each food group with its nutrient density as reported in the Global Expanded Nutrient Supply (GENuS) dataset, a global dataset of nutrient supply of 23 nutrients across 225 food categories for over 150 countries (Smith et al., 2016). For our analysis, we aggregated the nutrient dataset to the commodity and regional detail of our consumption data, and we normalised calorie densities to those of the Food and Agriculture Organization for consistency with our diet scenarios.

We compared the calculated nutrient content of the diet scenarios to recommendations of the World Health Organization (WHO) (Organization and others, 1996; WHO, 2003). Because the recommendations differ by age and sex, we calculated population-level average values for each nutrient by using the age and sex structure for the year of analysis based on data by the Global Burden of Disease project and forward projections by the Population Division of the United Nations (DeSA, 2013; Wang et al., 2016). Our estimates of recommended energy intake take into account the age and sex-specific energy needs for a moderately active population of US height as an upper bound (Health and Services, 2017; WHO, 2004), and include the energy costs of pregnancy and lactation (WHO, 2004). Our estimates of calcium intake take into account the average calcium content of drinking water, in line with previous assessments (Beal et al., 2017). Because the WHO did not set guidelines for phosphorus and copper, we adopted their recommended intakes from the US Institute of Medicine.

As proxies for consumption, we used projections from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) which uses economic, water, and crop models to simulate global food production, consumption, and trade of 62 agricultural commodities for 159 world regions (Robinson et al., 2015; Rosengrant and Team, 2012). We used the IMPACT model to produce global food scenarios for the year 2050. Building on methods developed by the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Nelson et al., 2014), we analysed the range of potential climate impacts by comparing a reference “middle-of-the-road” development scenario without climate-change impacts to scenarios with high climate-change impacts.

2.2. Climate-change analysis

In line with Springmann and colleagues (Marco Springmann et al., 2016), we adopted the highest emissions pathway (RCP8·5) to scope the full range of potential climate change impacts. That pathway leads to an increase in the global mean surface air temperature of 2·0 degrees C in 2046-2065 compared to the period 1986-2005 (Collins et al., 2013). Regional projections of the agricultural impacts of climate change are subject to significant uncertainty (Rosenzweig et al., 2014). We therefore used different combinations of general circulation models (GCMs), which project changes in temperature and precipitation, and crop models, which use those changes to project biophysical changes in crop yields, to generate a spread of input parameters for our agriculture and health assessment. The GCMs include HadGEM2ES (Jones et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2013), and MIROC-ESM-CHEM (Watanabe et al., 2011); and the crop models include DSSAT and LPJmL (Bondeau et al., 2007; Jones et al., 2003). The pair-wise combination of GCMs with crop models resulted in six climate change scenarios for each socio-economic and emissions pathway. We calculated the mean and standard deviation of the scenario endpoints that are associated with the different climate change scenarios.

In addition to the impacts that climate change is expected to have on crop yields, it can have an independent impact on the nutrient density of crops (Loladze, 2014; Myers et al., 2014b).

For our analysis, we adopted estimates by Myers and colleagues that specify the percentage reduction in iron, zinc, and protein in wheat, maize, rice, legumes and soybeans for elevated concentrations of carbon dioxide compared to current levels (Myers et al., 2014b). Table 1 provides an overview of the changes in nutrient levels used in this study.

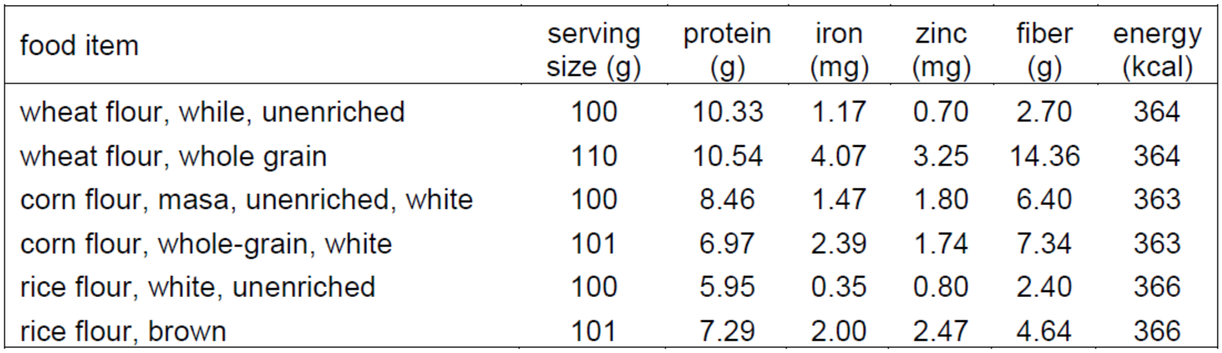
Table 1. Overview of changes in nutrient content (%) at elevated concentrations of carbon dioxide compared with ambient concentrations (adapted from Extended Data Table 4 from Myers and colleagues).

	protein			iron			zinc		
	mean	low	high	mean	low	high	mean	low	high
wheat	-6.3	-5	-8	-5.1	-4	-7	-9.3	-6	-12
rice	-7.8	-7	-9	-5.2	-3	-8	-3.3	-2	-5
maize				-5.8	-0	-11			
legumes	-2.1	-0	-12	-4.1	-1	-7	-6.8	-4	-10
soybeans				-4.1	-3	-6	-5.1	-4	-6

2.3. Diet scenarios

We specified two dietary adaptation scenarios to the climate change impacts on nutrient levels. The first one included a scenario in which all grains are consumed as whole grains. The GENuS dataset account for the proportion of grains consumed as whole grains and those consumed as refined one, based on regional processing estimates (Wessells et al., 2012). In the whole-grain diet scenario, we replaced, at equal calories, the nutrient densities of wheat, maize, and rice by those of whole grains adopted from the USDA nutrient database. According to those data (Table 2), whole-grain wheat has similar protein content, but 3-4 times more iron and zinc; whole-grain corn has similar zinc content, a fifth lower protein content, and two thirds higher iron content; and whole-grain (brown) rice has a fifth greater protein content, more than 5 times greater iron content, and 3 times greater zinc content.

Table 2. Nutrient content of refined and whole-grain varieties of wheat, corn, and rice flours as adopted from the USDA nutrient database.



food item	serving size (g)	protein (g)	iron (mg)	zinc (mg)	fiber (g)	energy (kcal)
wheat flour, while, unenriched	100	10.33	1.17	0.70	2.70	364
wheat flour, whole grain	110	10.54	4.07	3.25	14.36	364
corn flour, masa, unenriched, white	100	8.46	1.47	1.80	6.40	363
corn flour, whole-grain, white	101	6.97	2.39	1.74	7.34	363
rice flour, white, unenriched	100	5.95	0.35	0.80	2.40	366
rice flour, brown	101	7.29	2.00	2.47	4.64	366

In the second dietary adaptation scenario, we modelled more comprehensive dietary changes towards healthy diets. For that purpose, we adopted the dietary recommendations of a comprehensive review of the literature on healthy diets (Willett et al., 2019). The recommended dietary pattern from the review contains generous amounts of plant-based foods that have been associated with reductions in chronic-disease risk, such as fruits, vegetables, legumes, nuts, and (exclusively) whole grains; low amounts of foods that have been associated with increased risk, such as sugar and red and processed meat; and moderate amounts of other animal source foods (Table 3). The total energy content in the healthy-diet scenario was in line with recommendations of the energy needs of a moderately active population (Health and Services, 2017; WHO, 2004), and the dietary patterns were regionalised, at the country level, based on the age characteristics and the different energy needs in each region, and by preserving the current regional preferences for types of grains, fruits, red meat and fish.

Table 3. Overview of healthy diet scenario (flexitarian, FLX) compared to benchmark diets (BMK) in 2050 by food group and region, including a global average, diets in high-income countries (HIC), upper middle-income countries (UMC), lower middle-income countries (LMC), and low-income countries (LIC).

Food group	Global		HIC		UMC		LMC		LIC	
	BMK	FLX	BMK	FLX	BMK	FLX	BMK	FLX	BMK	FLX
wheat	126	86	142	150	151	127	132	77	67	42
rice	125	64	31	28	53	39	163	77	136	68
maize	39	25	17	18	76	54	27	15	68	39
other grains	33	18	11	11	12	9	31	15	69	37
roots	145	98	101	113	126	102	136	74	216	154
legumes	24	52	11	50	27	51	22	50	37	58
soybeans	7	25	3	25	2	25	11	25	2	25
nuts & seeds	7	51	7	50	2	50	7	51	8	51
sugar	64	30	67	30	106	31	65	31	31	25
palm oil	12	5	5	3	7	4	16	6	10	4
veg oil	19	42	39	49	28	42	14	40	10	40
vegetables	193	405	205	310	141	315	234	487	80	304
fruits (temp)	52	60	85	93	44	58	51	56	30	53
fruits (trop)	92	104	92	97	120	113	108	109	33	88
fruits (starchy)	41	44	17	20	46	46	36	45	73	59
beef	33	7	63	6	64	8	20	6	28	7
lamb	9	3	6	1	6	1	10	3	10	3
pork	34	4	71	7	30	4	33	4	14	3
poultry	43	24	82	29	80	29	35	26	15	13
eggs	23	11	30	13	28	13	26	12	7	6
milk	262	192	521	240	357	236	229	204	108	98

2.4. Dietary-risk analysis

In addition to changes in nutrient intake, climate change is expected to negatively impact dietary risk factors related to food consumption. Past studies have examined the association between climate change and changes in risk factors, such as the consumption of fruits, vegetables, and red meat (M. Springmann et al., 2016). Here we extend the analysis to also consider changes in whole grains and legumes. For analysing the implications of changes in dietary risks, we used comparative risk assessment framework with four risks (reductions in the consumption of fruits, vegetables, legumes, and whole grains) that are related to four disease endpoints (coronary heart disease, stroke, cancer, and type-2 diabetes). We adopted relative risk estimates that relate the risk factors to the disease endpoints from meta-analyses of prospective cohort studies (Afshin et al., 2014; Aune et al., 2017, 2016), and we used data from the Global Dietary Database (Micha et al., 2015) to allocate total grain consumption into whole grains and processed grains.

3. Results

According to our estimates (Table 4), without climate-change impacts, the average protein intake increased from 12% above recommended levels to 43% above recommended levels between 2010 and 2050, that of zinc increased from 73% above recommended levels to 100%, and that of iron increased from a potential shortfall of 6% to an intake that was 17% above recommended levels. Across regions, low-income countries exhibited potential protein deficiency in 2010, whereas high and middle-income countries exhibited potential iron deficiency in 2010.

Climate change reduced nutrient intake due to both reductions in crop yields and reductions in nutrient density (Table 4). On average, the percentage buffer of protein intake was reduced by 7 percentage points, that of zinc by 11 percentage points, and that of iron by 7 percentage points. The impacts on crop yields and those on nutrient density contributed approximately equally to the reduction in nutrient intake. Whilst most average intake values remained sufficient under climate change impacts, iron intake in high-income countries became more deficient, and iron intake in upper middle-income countries changes from average sufficiency to a potential shortfall in intake.

Dietary changes that replaced all refined grains with whole grains increased zinc and iron intake by 50-55% on average (Table 4). The potential shortfall in iron intake was reduced by over a third, and that in upper middle-income countries changed from potential shortfall into a buffer of 8% above recommended intake. Protein intake was reduced – by 4% on average, ranging from 27% in low-income countries to 1% in high-income countries – but it remained above recommended values in all aggregate regions. Dietary changes towards healthy diets led to less increases in iron and zinc, and larger reductions in protein, but nutrient intake was more equally distributed, with intake above recommended values in all aggregate regions.

Adequate nutrient intake at the regional level can hide potential shortfall at the country level (that in aggregate are compensated by buffers in other countries, e.g. from fortification). We therefore also analysed the number of countries with a potential shortfall in nutrients for the different scenarios and years of analysis (Table 5). According to our estimates, climate change impacts on yields and nutrient concentrations could increase the number of countries with protein deficiency by five countries (from 20 to 25) in 2050, those with iron deficiency by six (from 93 to 99), and those with zinc deficiency by 1 (from 5 to 6).

Table 4. Percentage deviation from recommended intake values for selected nutrients (protein, zinc, and iron) in the years 2010 and 2050 for a business-as-usual scenario without climate change (BMK), the mean climate-change impacts (averaged across 3 GCMs and 2 crop models) on agriculture yields and consumption along a business-as-usual socio-economic development pathway (SSP2_CC), and the mean climate change impacts on both crop yields and nutrient density (SSP2_CC_N).

Scenarios	proteir		zinc		iron	
	2010	2050	2010	2050	2010	2050
World						
BMK	23.09	42.51	72.77	99.83	-6.43	17.42
SSP2_CC		38.44		93.93		13.51
SSP2_CC_N		35.39		88.36		10.76
SSP2_CC_N_WGR		33.94		136.66		16.14
FLX		24.94		99.57		11.80
High-income countries						
BMK	38.63	45.82	85.51	93.79	-25.17	-18.11
SSP2_CC		43.33		89.98		-20.33
SSP2_CC_N		41.13		84.85		-22.15
SSP2_CC_N_WGR		40.57		113.73		-12.99
FLX		27.72		109.52		12.49
Upper middle-income countries						
BMK	50.64	68.75	111.42	134.84	-13.78	1.65
SSP2_CC		65.62		130.06		-0.95
SSP2_CC_N		63.03		123.89		-3.57
SSP2_CC_N_WGR		63.35		161.78		7.54
FLX		28.03		108.17		10.38
Lower middle-income countries						
BMK	18.94	45.50	69.95	103.59	-3.40	19.45
SSP2_CC		40.98		97.13		15.18
SSP2_CC_N		37.47		91.16		12.16
SSP2_CC_N_WGR		35.63		147.40		16.09
FLX		27.23		99.10		7.76
Low-income countries						
BMK	-6.51	14.37	29.18	69.46	6.54	44.08
SSP2_CC		9.81		62.96		39.21
SSP2_CC_N		7.28		58.94		36.56
SSP2_CC_N_WGR		5.30		104.69		39.10
FLX		13.95		86.61		22.86

Table 5. Number (#) and percent (%) of countries with potential shortfall in selected nutrients by year, scenario, and world region.

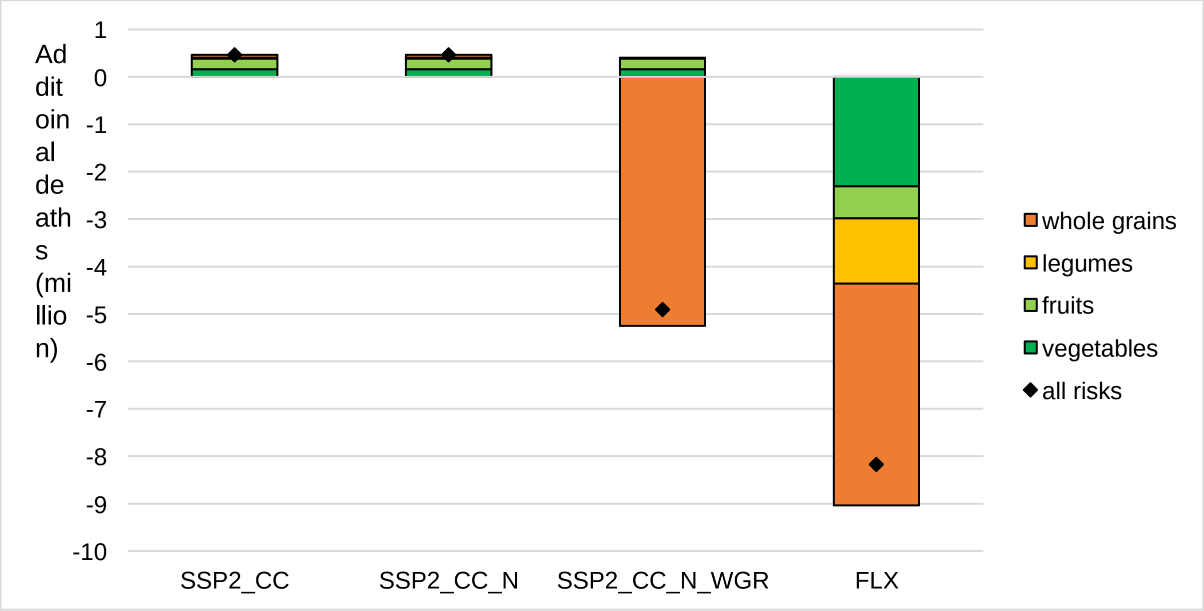
Scenarios	protein				iron				zinc			
	2010		2050		2010		2050		2010		2050	
	#	%	#	%	#	%	#	%	#	%	#	%
World												
BMK	51	33%	20	13%	122	79%	93	60%	16	10%	5	3%
SSP2_CC			24	15%			97	63%			5	3%
SSP2_CC_N			25	16%			99	64%			6	4%
SSP2_CC_N_WGR			29	19%			89	57%			4	3%
FLX			3	2%			33	21%			0	0%
High-income countries												
BMK	2	6%	2	6%	33	94%	29	83%	2	6%	2	6%
SSP2_CC			2	6%			29	83%			2	6%
SSP2_CC_N			2	6%			29	83%			2	6%
SSP2_CC_N_WGR			2	6%			28	80%			2	6%
FLX			0	0%			3	9%			0	0%
Upper middleincome countries												
BMK	4	13%	3	10%	26	84%	17	55%	2	6%	1	3%
SSP2_CC			3	10%			18	58%			1	3%
SSP2_CC_N			3	10%			18	58%			1	3%
SSP2_CC_N_WGR			3	10%			15	48%			1	3%
FLX			1	3%			5	16%			0	0%
Lower middleincome countries												
BMK	13	30%	5	11%	34	77%	26	59%	6	14%	1	2%
SSP2_CC			6	14%			27	61%			1	2%
SSP2_CC_N			6	14%			27	61%			2	5%
SSP2_CC_N_WGR			8	18%			25	57%			0	0%
FLX			1	2%			10	23%			0	0%
Low-income countries												
BMK	32	74%	10	23%	29	67%	21	49%	6	14%	1	2%
SSP2_CC			13	30%			23	53%			1	2%
SSP2_CC_N			14	33%			25	58%			1	2%
SSP2_CC_N_WGR			16	37%			21	49%			1	2%
FLX			1	2%			15	35%			0	0%

Dietary changes to whole grains could further increase protein deficiency by 4 countries, but reduce the number of countries with zinc and iron deficiencies by 2 and 10, respectively. In comparison, dietary changes to healthy diets led large reductions in the number of countries with inadequate intake of protein, iron, and zinc. Although iron intake in 33 countries (21% of all countries) still showed a potential shortfall in 2050, that number was a third of the number with potential shortfalls under climate change without targeted dietary changes.

In addition to the impacts of climate change on nutrient intake, the changes in food consumption impact diet-related risk factors that affect chronic-disease mortality. According to our estimates, climate change could lead to about 460,000 (436,00-492,000) additional deaths in 2050 (Figure 1). About half of the additional deaths were from reduced fruit intake, a third from reduced vegetable intake, 4% due to reduced intake of legumes, and 13% due to reductions in whole-grain intake assuming the ratio between whole grain and refined grains stays the same. More than two thirds (71%) of the additional deaths occurred in lower middle-income countries, and 8-11% each in the other income regions.

Dietary changes that replace all refined grains with whole grains mitigated, in most regions, the climate-related increases in dietary risks and led to a number of avoided deaths that was ten times greater in total (4.9 million, 4.4-5.4) than the number of additional deaths that climate change led to. The number of countries with climate-related deaths was reduced from 130 to 12. Comprehensive dietary changes to healthy diets further increased the number of avoided deaths by an additional two thirds (8.2 million, 7.6-8.8), and it reduced the number of countries with climate-related deaths to zero.

Figure 1. Additional deaths from chronic disease related to changes in diet-related risk factors in 2050 by scenario and risk factor.



4. Discussion

Climate change is expected to have detrimental impacts on food security, including on nutrient availability, due to reductions in crop yields and nutrient concentrations of crops (Myers et al., 2014a; M. Springmann et al., 2016). Production-level interventions, such as breeding of climate-resilient crop varieties, are important adaptation strategies, in particular for addressing the yield impacts of climate change (Beach et al., 2019; Islam et al., 2016). Our results suggest that complementing such strategies by interventions at the consumption level could help mitigate the nutrient impacts of climate change, whilst improving dietary health and, for the case of comprehensive dietary changes towards healthy and sustainable diets, contribute to climate-change mitigation (Springmann et al., 2018b).

Amongst the two dietary-change strategies, we found that consuming all grains as whole grains compensated the negative impacts climate change could have on zinc and iron intake, whilst more comprehensive dietary changes towards healthy and sustainable diets led to additional reductions in potential zinc and iron deficiencies, whilst also improving protein deficiencies. In addition, both strategies improved dietary risks and reduced chronic-disease mortality, thereby compensating the additional impacts that climate change could have on dietary risks (M. Springmann et al., 2016).

The two strategies differ with respect to the costs of implementation. Comprehensive dietary changes are hard to achieve and likely require a combination of progressive food policies to be successful (Mozaffarian, 2016; Mozaffarian et al., 2012). Changing grains consumption from a mix of refined and whole grains towards more whole grains is more limited and scope and therefore potentially easier to achieve by targeted interventions, comparable perhaps to those aimed at replacing white-flashed sweet potatoes with more nutritious orange-fleshed varieties (Jenkins et al., 2015). A more targeted intervention focused on one food group can also be expected to have less impacts on food prices and the costs of diets. A recent modelling study has found that healthier and more sustainable diets could be associated with cost reductions in high and middle-income countries, but costs could increase in low-income settings as diets diversify (Springmann et al, *under review*).

Instead of an either-or approach, a time-staggered one might be more appropriate, including a short-term aim of increasing the ratio of whole grains to refined grains in diets, and following a medium to long-term aim of increasing the general healthiness and sustainability of diets. This approach would have the additional benefits of contributing to levels of resource use in line with the sustainable-development agenda and global environmental limits (Nations, 2015; Springmann et al., 2018a), whilst adopting a practical and targeted dietary-change agenda in the short term.

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Notes

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