

Article

# The Mismatch between Anthropogenic CO<sub>2</sub> Emissions and Their Consequences for Human Zinc and Protein Sufficiency Highlights Important Environmental Justice Issues

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**Abstract:** The impacts of climate change are not equally distributed globally. We examined the global distribution of CO<sub>2</sub> emissions and the ensuing distribution of increases in the risk of zinc and protein deficiency resulting from elevated atmospheric CO<sub>2</sub> concentrations. We estimated cumulative per capita (2011–2050) CO<sub>2</sub> emissions for 146 countries using existing measurement data and by apportioning regional emissions projections. We tested the relationship between cumulative per capita CO<sub>2</sub> emissions and the risk of additional zinc and protein deficiency at the population-level and country-level. At the population-level (i.e., population-weighted), we observed a significant inverse association between CO<sub>2</sub> emissions and the percentage of the population placed at additional risk of zinc (*p*-value: <0.001) and protein (*p*-value: <0.01) deficiencies. Country-level (i.e., unweighted) analyses produced significant but less strong associations. Populations with lower per capita CO<sub>2</sub> emissions between 2011 and 2050 will experience a disproportionately high nutritional burden, highlighting socioeconomic, geospatial, and intergenerational injustices.

**Keywords:** climate change; nutrition; environmental justice

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## 1. Introduction

The impacts of climate change are not equally distributed globally. Countries with the highest historical greenhouse gas emissions have been found to be the least vulnerable to the negative impacts of climate change—such as extreme weather events, impacts on the food system, biodiversity loss, economic stress, and health effects [1]. In contrast, low-emitting countries tend to be the most vulnerable. Climate change is expected to impact human health by changing the severity or frequency of already occurring health problems and/or by creating unanticipated health threats [2,3]. Numerous recent reports highlight the large human health risks associated with intensifying climatic disruption and differential exposure to such risks for some people and communities [4,5]. While all countries are at risk of the health impacts of climate change, low-income and marginalized populations are most vulnerable [1–6]. In the food systems literature, it is documented that climate change has the

potential to impact food availability and may exacerbate food insecurity in predominantly low-income countries [7–9].

In addition to these well-documented risks to human health from climate change, human nutritional adequacy is also likely to be affected by the impact of rising atmospheric CO<sub>2</sub> concentrations on the nutritional content of many food crops. Combined free air CO<sub>2</sub> enrichment (FACE) experiments for a variety of crops document that atmospheric concentrations of 550 parts per million (ppm) of CO<sub>2</sub> (hereafter referred to as elevated CO<sub>2</sub>) can induce significant decreases in the zinc and protein content of C<sub>3</sub> grasses (for example, wheat and rice) [10–12], pulses and legumes (peas and beans) [10,11], and C<sub>3</sub> fruits and vegetables (includes nearly all plants in these food groups) [11]. On our current global emissions trajectory (following a business-as-usual approach), we are predicted to reach this atmospheric CO<sub>2</sub> concentration by roughly 2050 [13].

Modeling studies examining the global health implications of these changes found that by 2050 the decreased zinc content in foods could put 175 million people globally at new risk of zinc deficiency and 122 million at new risk of protein deficiency [14]. Other models have estimated that the decreased crop zinc and iron concentrations attributable to elevated atmospheric CO<sub>2</sub> concentrations could lead to an additional 125.8 million disability-adjusted life years globally from 2015 to 2050 [15]. Inadequate zinc intake in children is associated with pneumonia, malaria, and diarrheal disease [16], and may contribute to low birthweight and altered immunity and metabolic status among offspring when occurring prior to or during pregnancy [17]. Inadequate protein intake is known to contribute to wasting, stunting, intrauterine growth restriction, and low birthweight [16]. Although inadequate zinc and protein intakes are prevalent around the world, models predict larger increases in the prevalence of nutritional inadequacy for countries in Sub-Saharan Africa and South Asia and in countries that primarily rely on plant-based sources of protein [14].

Here we investigate the country-specific association between current and future cumulative per capita CO<sub>2</sub> emissions and increases in risk for zinc and protein deficiencies associated with rising CO<sub>2</sub> levels. We hypothesize that countries and people that have contributed the least to global CO<sub>2</sub> emissions between 2011 (baseline) and 2050 (elevated CO<sub>2</sub>) will bear a disproportionate nutritional burden from rising atmospheric CO<sub>2</sub> concentrations.

## 2. Results

Table 1 describes the populations, cumulative per capita CO<sub>2</sub> emissions, and the estimates of increased prevalence of dietary zinc and protein inadequacy according to World Bank Income Groups [13] and selected countries within income groups (also see Figure S1). Globally, in 2011, we estimated population-weighted average per capita CO<sub>2</sub> emissions of 4.3 metric tons of CO<sub>2</sub> (MtCO<sub>2</sub>), increasing to 4.6 MtCO<sub>2</sub> in 2050. Meanwhile, the global population-weighted percent increase in those newly at risk of zinc deficiency is modeled to be 1.8% (95% CI: 1.6–1.9%) and the population-weighted percent increase in those newly at risk of protein deficiency is modeled to be 1.3% (95% CI: 1.2–1.4%) over the same timeframe.

At the country level (i.e., not population-weighted), we found a significant inverse association between cumulative (2011–2050) per capita CO<sub>2</sub> emissions and increased risk of zinc ( $R^2$ : 0.06;  $p$ -value: <0.01) and protein ( $R^2$ : 0.03;  $p$ -value: 0.03) deficiency (Table 2).

**Table 1.** Populations, cumulative per capita CO<sub>2</sub> emissions, and increased population at risk of zinc and protein deficiency resulting from elevated CO<sub>2</sub> between 2011 and 2050, by income group.

Income Groups [18]	Population 2011 Excluding Countries with Missing Data (Thousands) <sup>a,b</sup>	Population 2050 Excluding Countries with Missing Data (Thousands) <sup>a,c</sup>	Population 2050 Complete Population Prospects (Thousands) <sup>c</sup>	Per Capita CO <sub>2</sub> in 2011 (MtCO <sub>2</sub> )	Per Capita CO <sub>2</sub> in 2050 (MtCO <sub>2</sub> )	Cumulative Per Capita CO <sub>2</sub> (2011–2050) (MtCO <sub>2</sub> )	% Increase in Prevalence of Zinc Deficiency (95% CI) [14]	% Increase in Prevalence of Protein Deficiency (95% CI) [14]
World <sup>d</sup>	6,576,127	8,864,390	9,770,817	4.3	4.6	172	1.8% (1.6–1.9)	1.3% (1.2–1.4)
High-Income <sup>d</sup>	1,157,231	1,296,592	1,352,321	12.0	10.8	433	0.7% (0.5–0.8)	0.5% (0.4–0.5)
Australia	22,480	33,187	33,187	18.0	16.4	639	0.3% (0.3–0.3)	0.1% (0.1–0.2)
Canada	34,539	44,949	44,949	16.2	14.9	618	0.6% (0.5–0.6)	0.3% (0.2–0.4)
Japan	128,505	108,794	108,794	9.8	8.7	346	1.5% (1.3–1.7)	0.7% (0.5–1.0)
New Zealand	4418	5711	5711	7.8	8.5	308	0.3% (0.2–0.3)	0.1% (0.0–0.1)
South Korea	49,745	50,457	50,457	11.8	18.4	587	1.2% (1.1–1.4)	0.7% (0.4–1.0)
United States	311,051	389,592	389,592	17.9	13.0	585	0.3% (0.2–0.3)	0.5% (0.3–0.8)
Upper Middle-Income <sup>d</sup>	2,477,165	2,757,330	2,769,833	6.1	6.5	250	1.5% (1.2–1.7)	1.3% (1.1–1.4)
Brazil	198,687	232,688	232,688	2.2	2.9	100	0.8% (0.7–0.9)	0.5% (0.3–0.8)
China	1,367,480	1,364,457	1,364,457	7.1	7.2	288	1.2% (1.0–1.5)	1.6% (1.1–2.1)
Mexico	119,090	164,279	164,279	4.1	3.3	133	2.2% (1.9–2.6)	0.3% (0.2–0.5)
Russian Federation	143,264	132,731	132,731	12.0	11.6	458	0.8% (0.7–0.9)	1.0% (0.5–1.5)
Lower Middle-Income <sup>d</sup>	2,503,334	3,817,825	4,126,176	1.4	2.2	69	2.3% (2.1–2.5)	1.7% (1.4–1.9)
India	1,247,236	1,658,978	1,658,978	1.5	3.0	87	2.7% (2.4–2.9)	2.1% (1.4–2.9)
Low-Income <sup>d</sup>	405,538	948,282	1,509,883	0.3	0.2	11	2.1% (1.8–2.3)	1.0% (0.7–1.3)

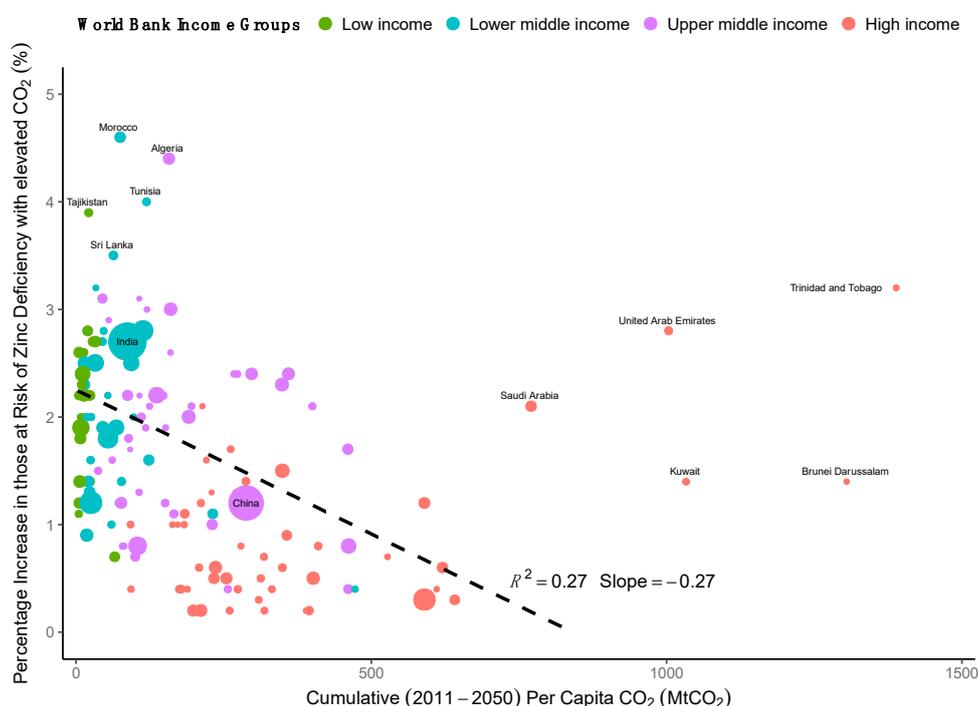
Note. CO<sub>2</sub> = Carbon dioxide; MtCO<sub>2</sub> = Metric tons of carbon dioxide; <sup>a</sup> Excludes countries with incomplete data on CO<sub>2</sub> and zinc or protein inadequacy; <sup>b</sup> United Nations 2017 World Population Prospects [19] total Population Estimates for 1950–2015; <sup>c</sup> United Nations 2017 World Population Prospects [19] probabilistic median for 2050; <sup>d</sup> Per capita CO<sub>2</sub> and estimates of the % increase in prevalence of those newly at risk of zinc and protein deficiency using population weights from the United Nations 2017 World Population Prospects [19] probabilistic median for 2050.

At the population level (i.e., population-weighted), we found a significant inverse linear relationship between cumulative per capita CO<sub>2</sub> emissions and increased risk of zinc deficiency (R<sup>2</sup>: 0.27, p-value: <0.001) (Table 2 and Figure 1). We found that each increase in cumulative (2011–2050) per capita CO<sub>2</sub> emissions of 100 MtCO<sub>2</sub> was associated with a 0.27 percent decrease in those at new risk of zinc deficiency (Table 2 and Figure 1).

**Table 2.** Unweighted and population-weighted associations between cumulative per capita CO<sub>2</sub> emissions and increased population newly at risk of zinc and protein deficiency between 2011 and 2050, for 146 countries and for a subset of 141 countries that excludes outlying highest cumulative per capita CO<sub>2</sub> emitters.

Regressor	N	Slope (SE) <sup>a</sup>	R <sup>2</sup>	p-Value
<b>Risk of Zinc Deficiency</b>				
Unweighted	146	−0.10 (0.03)	0.06	<0.01 *
Population-weighted <sup>b</sup>	146	−0.27 (0.04)	0.27	<0.001 *
Unweighted with outliers removed	141	−0.31 (0.05)	0.25	<0.001 *
Population-weighted with outliers removed <sup>b</sup>	141	−0.32 (0.04)	0.32	<0.001*
<b>Risk of Protein Deficiency</b>				
Unweighted	146	−0.06 (0.03)	0.03	0.03 *
Population-weighted	146	−0.11 (0.03)	0.07	<0.01 *
Unweighted with outliers removed	141	−0.15 (0.04)	0.09	<0.001 *
Population-weighted with outliers removed <sup>b</sup>	141	−0.12 (0.04)	0.07	<0.01*

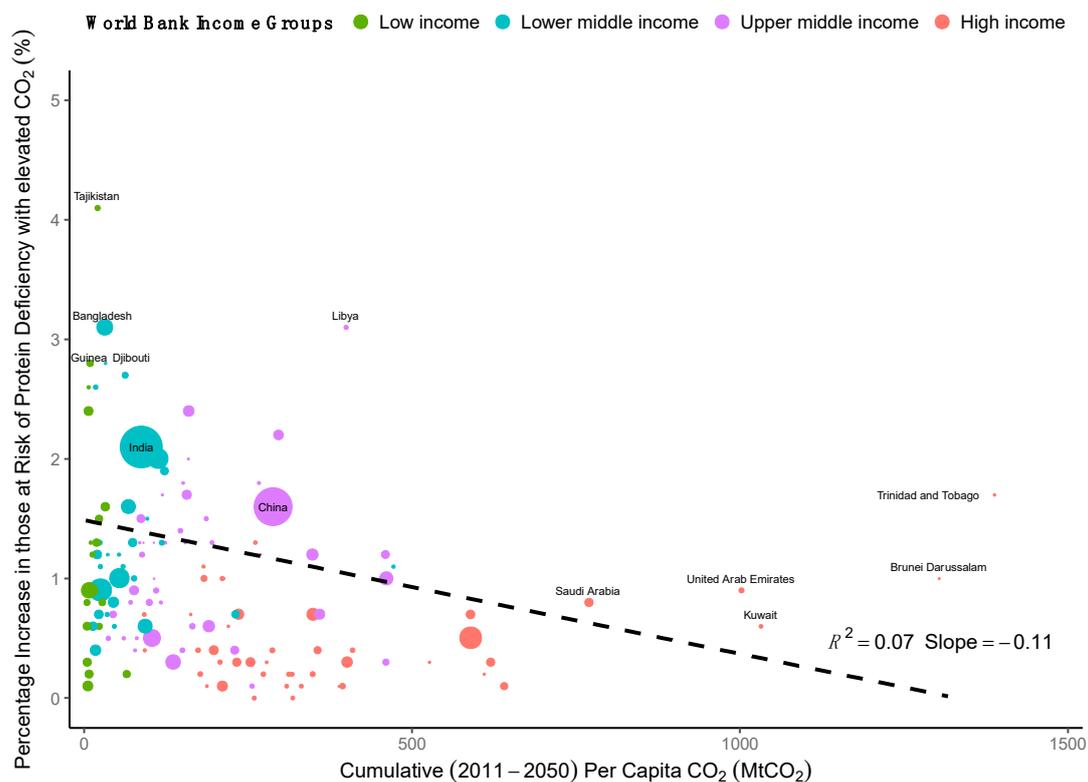
<sup>a</sup> Values represent change in prevalence in the risk of deficiency (percent) per 100 MtCO<sub>2</sub> increase in cumulative per capita CO<sub>2</sub>; <sup>b</sup> Population weights from the United Nations 2017 World Population Prospects [19] probabilistic median for 2050. \* Indicates significance.



**Figure 1.** Population-weighted association between cumulative per capita CO<sub>2</sub> emissions and percentage increase in the population at risk of zinc deficiency with elevated CO<sub>2</sub> for 146 countries between 2011 and 2050 with select individual countries labeled. Bubble sizes depict the population prospect for each country in 2050 [19]. Note. CO<sub>2</sub> = Carbon dioxide; MtCO<sub>2</sub> = Metric tons of carbon dioxide.

For protein, at the population level (i.e., population-weighted), we similarly found a significant inverse linear relationship between cumulative per capita CO<sub>2</sub> emissions and increased risk of protein deficiency ( $R^2$ : 0.07,  $p$ -value: <0.01) (Table 2 and Figure 2). Each 100 MtCO<sub>2</sub> increase in cumulative per capita CO<sub>2</sub> emissions was associated with a 0.11 percent decrease in those at new risk of protein deficiency (Table 2 and Figure 2).

For both zinc and protein, these findings show that countries with lower per capita CO<sub>2</sub> emissions have a higher modeled increase in future new risk of deficiency.



**Figure 2.** Population-weighted association between cumulative per capita CO<sub>2</sub> emissions and percentage increase in the population at risk of protein deficiency with elevated CO<sub>2</sub> for 146 countries between 2011 and 2050 with select individual countries labeled. Bubble sizes depict the population prospect for each country in 2050 [19]. Note. CO<sub>2</sub> = Carbon dioxide; MtCO<sub>2</sub> = Metric tons of carbon dioxide.

The global associations between population-weighted cumulative per capita CO<sub>2</sub> and the populations newly at risk of zinc and protein deficiencies are shown in Figures 1 and 2. For zinc, Morocco, Algeria, Tunisia, Tajikistan, and Sri Lanka had the greatest inequality in the burden of increased risk of deficiency relative to cumulative per capita CO<sub>2</sub>. For protein, Tajikistan, Bangladesh, Guinea, and Djibouti, had the greatest inequality in the burden of increased risk of deficiency relative to cumulative per capita CO<sub>2</sub>. We labeled India and China separately as previous work found that increased CO<sub>2</sub> could put 49.6 million at new risk of zinc deficiency and 38.2 million at new risk of protein deficiency in India and 18.3 million at new risk of zinc deficiency and 22.1 million and new risk of protein deficiency in China [14]. We also highlight India and China to draw attention to their potential nutritional vulnerabilities relative to their estimated future CO<sub>2</sub> emissions and to point out the important influence they may have on our non-population weighted results.

Our sub-analyses excluding the five countries with the highest cumulative per capita CO<sub>2</sub> (N = 141) emissions indicated a significant negative association between cumulative per capita CO<sub>2</sub> and dietary zinc and protein inadequacy. At the population level (i.e., population-weighted), the risk of zinc deficiency decreased 0.32 percent per 100 MtCO<sub>2</sub> increase in cumulative per capita CO<sub>2</sub> ( $R^2$ : 0.32;

$p$ -value:  $<0.001$ ). For protein, our population-weighted results did not meaningfully change after excluding the five outliers. The slope decreased slightly from  $-0.11$  to  $-0.12$ , but our variance estimates remained low ( $R^2$ : 0.07;  $p$ -value: 0.01).

### 3. Discussion

We found that the predicted increased risk of zinc and protein deficiencies in a higher CO<sub>2</sub> world will not be equitably distributed. Populations with lower CO<sub>2</sub> emissions will bear a disproportionate burden. In the climate change context, distributive justice is defined as the proportional distribution of greenhouse gas emissions and their associated benefits and harms [20]. Our findings highlight three dimensions of distributive injustice: socioeconomic, geospatial, and intergenerational. Poorer populations (which tend to have lower per capita CO<sub>2</sub> emissions), particular countries and regions, and future generations will bear much of the ensuing burden of CO<sub>2</sub> emissions, which are emanating in the present from wealthier populations and regions.

Our findings are most likely an underestimate of distributive injustice because of heterogeneity within countries. In our methodology, we examined aggregate country-level data and apportioned it to the individuals based on population projections (i.e., the population-weighted analyses); however, the per capita CO<sub>2</sub> emissions and increased risk of zinc and protein deficiency will not be distributed equally within countries. Food insecure and nutritionally inadequate populations within countries may experience exacerbated risk of inadequate zinc and protein intakes with rising CO<sub>2</sub> concentrations. Some very populous countries—such as India and China—have especially large within-country differences in wealth and diet quality. It may be that within these large heterogeneous countries there are a minority of wealthier high-CO<sub>2</sub>-emitting sub-populations that would see very little adverse nutritional consequence as a result of higher CO<sub>2</sub>, whereas there are much larger poorer sub-populations—collectively the source of very little CO<sub>2</sub>—that will likely suffer the bulk of adverse nutritional consequences of rising CO<sub>2</sub> levels. Because the data used to populate the models is at the country level, we are unable to assess these sub-country effects, but they have the potential to exacerbate the broader trends described here.

These findings build on previous modeling work [14,15] to quantify the inequalities in the nutritional impacts of climate change and add to our understanding of climate justice. This work shows that the countries and people that have contributed the least to global rising CO<sub>2</sub> emissions are likely to be at the greatest risk of increased zinc and protein inadequacy and underscores the need for substantial greenhouse gas mitigation and adaptation efforts and also greater attention to redressing such injustices across countries. Our work also adds evidence that low-income countries are differentially exposed to the adverse health impacts of climate change. Further, because the potential changes to zinc and protein inadequacy are modeled to occur at a higher CO<sub>2</sub> concentration (550 ppm), our work suggests the burden of increased zinc and protein inadequacy will be endured in the future and shouldered by future generations.

There are several limitations to our analysis. We aggregated data from multiple sources, and thus our analysis is subject to the limitations and assumptions made by each source. The Global Carbon Atlas [21] uses three CO<sub>2</sub> data sources [22–24], and the estimates for 2015 and 2016 were preliminary at the time of our analysis. Several assumptions were made to estimate annual country-specific CO<sub>2</sub> emissions from 2017 to 2050. First, the region-specific projections obtained from the US Energy Information Administration *International Energy Outlook 2017* report [25] are subject to uncertainty. The International Energy Outlook (IEO) model used to create the long-term projections makes assumptions about economic growth, population, world oil prices, and regulations and policies that are highly contingent on a variety of factors and subject to change [26]. Second, we used 2016 CO<sub>2</sub> emissions to estimate the per-country share of the IEO regional CO<sub>2</sub> projections. CO<sub>2</sub> emissions are a result of a combination of economic growth, population, energy sources, policies, and several other factors, and it is unlikely that the country-specific share of CO<sub>2</sub> emissions will be constant between 2016 and 2050. We used the United Nations *World Population Prospects: The 2017 Revision* [19] to 2050 to

estimate cumulative per capita emissions and future population-weights, which are based on uncertain assumptions about future fertility and life expectancy.

Our analysis is also limited by the assumptions used to model increased prevalence of dietary zinc and protein inadequacy with elevated CO<sub>2</sub> [14]. These models did not account for substitution or changes in diet and used binary categorization of dietary zinc and protein inadequacy. As with CO<sub>2</sub> emissions, environmental, economic, and policy changes may potentially impact future diets and would alter our findings. The FACE experiment data used to populate the models primarily came from high-income nations with excellent soil conditions. Impoverished soil is often a source of poor agricultural performance, and it is uncertain how the changes in zinc and protein content of foods due to increased CO<sub>2</sub> concentrations could vary by soil conditions. The estimated increases in those at risk of zinc and protein deficiency also neglect large populations that are already nutritionally deficient—at least 1.5 billion people are currently deficient in one or both nutrients—that may see their deficiencies worsen [14].

We limited our analysis to zinc and protein inadequacy. While FACE experiments found that iron and several vitamins will decrease with elevated CO<sub>2</sub> concentrations, due to insufficient global information on other dietary factors that affect the absorption of iron that we would need to model the increase in iron inadequacy (e.g., polyphenols, alcohol) [14], we concentrated on nutrients for which we are capable of accurately predicting bioavailability.

We rely on simple linear regression models to ease the interpretation of our results. Our results show that CO<sub>2</sub> emissions explain a portion of the variability in future zinc and protein inadequacy, but there are undoubtedly multiple factors that will influence future zinc and protein adequacy apart from CO<sub>2</sub> emissions. This work does not seek to incorporate these factors, which could include increasingly degraded soils, extensification into marginal farmlands, increased use of agrochemicals or advanced farming techniques, or improved crop cultivars. Instead, we opt for transparent assumptions that allow us to highlight that the distribution of nutritional impacts resulting from elevated CO<sub>2</sub> emissions will not be equitably distributed, with an inverse relationship between those experiencing the benefits and burdens.

Future research is needed to explore how elevated CO<sub>2</sub> will impact other nutrients, alter plant stoichiometry, and contribute to multiple nutritional deficiencies. Within-country differences in increased risk of nutritional inadequacy resulting from elevated CO<sub>2</sub> and sub-populations that are at increased risk also need to be examined. Because there may be regional disparities in the CO<sub>2</sub> fertilization effect and crop yields [27], future research should explore how changes to the nutritional content of crops and changes in crop yield due to elevated CO<sub>2</sub> concentration may interact.

## 4. Materials and Methods

### 4.1. Data Sources

#### 4.1.1. Increased Prevalence of Dietary Zinc and Protein Inadequacy with Elevated CO<sub>2</sub> Concentrations

We used previously published data [14], derived from analyses employing the Global Expanded Nutrient Supply (GENUS) model datasets [28], for the potential per-country increase in those newly at risk of zinc deficiency and protein deficiency caused by elevated CO<sub>2</sub> concentrations. A full description of their methods may be found in the original publication, but the following is a brief summary [14]. Previous studies [10–12,14,15] have found that an elevated CO<sub>2</sub> concentration of 550 ppm can reduce the zinc and protein content of many staple crops by up to 17% relative to ambient conditions of 363–386 ppm. Based on our current global emissions trajectory, we will reach 550 ppm CO<sub>2</sub> by roughly mid-century [13]. Smith and Myers applied the nutritional losses in crops to per capita nutritional intakes from 2011 to estimate the relative decline in intake under elevated CO<sub>2</sub>, assuming constant diets into the future [14]. While diets will change in the future, the direction of these changes is unpredictable; therefore, the authors assumed static diets to provide estimates that did not assume the directionality of dietary trends. To estimate the risk of additional nutritional inadequacy resulting

from the increase in CO<sub>2</sub>, they compared current and future nutrient intakes to population-weighted estimated average requirements [29] for each population group and country. This methodology estimates the size of the population that is consuming an inadequate amount of each nutrient compared to their physiologic needs, which is similar, but not directly equivalent, to the prevalence of nutritional deficiency. Therefore, we describe this population throughout this paper either as being newly at risk of deficiency or consuming inadequate amounts of these dietary nutrients. The prevalence of inadequate intakes was estimated under current and future conditions, and the relative increase in inadequacy was estimated by subtracting the two. To account for the uncertainty in future estimates caused by variability in the nutrient density of foods, as well as the response of crop nutrition to elevated CO<sub>2</sub>, they used Monte Carlo simulations (N = 1000) to establish a range of possible values for the increased risk of zinc and protein deficiency. We used the country-specific median percent increase in the prevalence of zinc and protein inadequacy resulting from elevated CO<sub>2</sub> (referred to as the increased prevalence in zinc and protein inadequacy), from the range of possible values provided by the Monte Carlo simulations. Data from 151 countries were available.

#### 4.1.2. Country-Specific Cumulative CO<sub>2</sub> Emissions

We estimated country-specific cumulative CO<sub>2</sub> emissions from 2011–2050. Annual CO<sub>2</sub> emissions from 2011–2016 for 220 countries and territories were obtained from the Global Carbon Atlas [21], which is aggregated from several sources [22–24]. To estimate country-specific CO<sub>2</sub> emissions for 2017–2050, we began with regional projections of annual CO<sub>2</sub> emissions for these years from the US Energy Information Administration *International Energy Outlook 2017* (IEO) report [19]. Then, we apportioned the projected annual emissions for each IEO region amongst its constituent countries according to each country's share of the regional emissions in 2016. Some countries are their own "region" in the IEO report (e.g., Canada, China, India, United States of America) and are treated individually. Consistent with the IEO regional definitions, we included Israel in the OECD Europe region and considered Latvia in the non-OECD Europe and Eurasia region [19]. This methodology produced 2017–2050 CO<sub>2</sub> emissions estimates for 212 countries.

We then summed the country-specific observed 2011–2016 annual CO<sub>2</sub> emissions and the country-specific projected annual 2017–2050 emissions across all years to obtain country-specific 2011–2050 cumulative CO<sub>2</sub> emissions estimates. While cumulative CO<sub>2</sub> captures the amount of emissions a country will contribute to the global total, it does not take into account population size. As our study assesses environmental justice and nutritional impacts, per capita CO<sub>2</sub> provides a more relevant comparison of CO<sub>2</sub> emissions. For example, Nigeria has high cumulative CO<sub>2</sub> emissions (2011–2050) but low per capita CO<sub>2</sub> emissions because of its large population, while Saudi Arabia has high cumulative CO<sub>2</sub> emissions (2011–2050) and high per capita CO<sub>2</sub> emissions because of its smaller population. To estimate cumulative per capita CO<sub>2</sub> emissions, we divided country-specific cumulative CO<sub>2</sub> emissions by the respective country's population prospects [21] for each year in our study. We summed each year's per capita CO<sub>2</sub> to estimate the country-specific cumulative per capita CO<sub>2</sub> emissions (2011–2050). The United Nations' world population median projection for 2050 of 9.8 billion [19] is greater than the population used in our study (8.9 billion) because we excluded the populations of countries that had incomplete CO<sub>2</sub> emissions or incomplete risk of increased zinc or protein deficiency data (Table 1).

We used the World Bank Income Groups [18], which are determined yearly using gross national income per capita, to group countries of similar economies. Countries are designated as one of four income groups: high-income, upper-middle income, lower-middle income, low-income.

#### 4.2. Statistical Analysis

We assessed the relationship between cumulative per capita CO<sub>2</sub> emissions (2011–2050) and the increased population at risk of zinc and protein deficiency using linear regression models for all countries for which we had both cumulative CO<sub>2</sub> emissions and nutritional data (N = 146). Because the

increase in the population at risk of deficiency varied greatly between countries even within the same region, we use country and not region as our unit of data analysis (see full country data in Supplement Table S1).

We used simple linear regression models to test if the countries that emit lower cumulative per capita CO<sub>2</sub> are more or less likely to experience increased risk of zinc and protein deficiency in 2050. We ran models both with and without population weighting of the countries to test the strength of the relationship both at the country and population scales. Without population-weighting, a small country (e.g., Belize) and a large country (e.g., India) are treated equally. However, the number of people newly at risk of deficiency are of course more numerous in large countries than small ones, which is why population-weighting provided an insightful measure. We established population weights using the probabilistic median country-specific populations of the United Nations World Population Prospects for 2050 [19].

To assess the impact of anomalous per capita CO<sub>2</sub> emissions by outlier nations, we also ran regressions with and without five outlier high-emitting nations: Trinidad and Tobago, Brunei Darussalam, Kuwait, the United Arab Emirates, and Saudi Arabia. As seen in Figure 1, these countries have anomalously high per capita emissions, due to their high fossil fuel consumption, energy-intensive production of fossil fuels, high overall wealth, and relatively small population sizes.

All statistical analyses were conducted using R *Version* 3.4.3. Geographic presentation of data used the Rworldmap package. The data that support the findings of this study are available in the Supplementary Information, Table S1.

## 5. Conclusions

We examined the relationship between projected cumulative per capita CO<sub>2</sub> emissions from 2011–2050 and modeled increases in those at potential risk of zinc deficiency and protein deficiency if CO<sub>2</sub> concentrations reach 550 ppm, at the country and population levels. We found socioeconomic, geospatial, and intergenerational injustices in the distribution of impacts of CO<sub>2</sub> emissions on increased risks of zinc and protein deficiency. This work highlights that mitigating CO<sub>2</sub> emissions by the highest emitters is not only a high global health and environmental priority but also a moral imperative.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2078-1547/11/1/4/s1>, Table S1: Country-specific cumulative per capita CO<sub>2</sub> emissions from 2011–2050 and the modeled increased prevalence of those at risk of zinc and protein deficiency resulting from elevated atmospheric CO<sub>2</sub> concentrations. Figure S1: Maps showing cumulative per capita CO<sub>2</sub> (A), the percent increase in prevalence of those at risk of zinc deficiency (B), and the percent increase in those at risk of protein deficiency (C) with a CO<sub>2</sub> concentration of 550 parts per million.

**Author Contributions:** E.R.H.M. led the analyses and writing. M.R.S. assisted with the study, writing, and analyses. D.H., R.D., and S.S.M. contributed to the design and interpretation of the study. M.R.S. and S.S.M. provided the nutritional data. All authors contributed to the analysis and interpretation of the data and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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