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Impact of anthropogenic CO_2 emissions on global human nutrition

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Atmospheric CO_2 is on pace to surpass 550 ppm in the next 30–80 years. Many food crops grown under 550 ppm have protein, iron and zinc contents that are reduced by 3–17% compared with current conditions. We analysed the impact of elevated CO_2 concentrations on the sufficiency of dietary intake of iron, zinc and protein for the populations of 151 countries using a model of per-capita food availability stratified by age and sex, assuming constant diets and excluding other climate impacts on food production. We estimate that elevated CO_2 could cause an additional 175 million people to be zinc deficient and an additional 122 million people to be protein deficient (assuming 2050 population and CO_2 projections). For iron, 1.4 billion women of childbearing age and children under 5 are in countries with greater than 20% anaemia prevalence and would lose >4% of dietary iron. Regions at highest risk—South and Southeast Asia, Africa, and the Middle East—require extra precautions to sustain an already tenuous advance towards improved public health.

Global emissions of CO_2 are at record highs[1], resulting in the largest measured global concentrations of atmospheric CO_2 in modern times, surpassing 400 ppm in 2016[2]. In the absence of stringent mitigation efforts, atmospheric CO_2 is expected to rise through at least 2100, with the upper limit of models predicting concentrations of nearly 940 ppm by the end of the century[3]. Due to the steady growth of CO_2 emissions from fossil fuel use[4] and land-use change[5], the trend of measured CO_2 emissions has remained in line with the most alarming model forecast (Fig. 1)[1,3]. Based on every scenario except the most optimistic, we are expected to reach 550 ppm by roughly the end of this century. Under the scenario most consistent with our current trajectory (Representative Concentration Pathway (RCP) 8.5), we anticipate reaching 550 ppm by the middle of the century.

Anthropogenic CO_2 emissions threaten human nutrition via two distinct pathways: (1) disrupting the global climate system with all the associated impacts on food production[6]; and (2) directly altering the nutrient profile of staple food crops. In particular, experimental trials in which crops are grown in open field conditions under both ambient and elevated CO_2 have revealed that many important food crops have 3–17% lower concentrations of protein, iron and zinc (Supplementary Table 3) when grown under elevated CO_2 levels of ~550 ppm (hereafter, eCO_2)[7,8].

This effect is likely to reduce the dietary supply of nutrients for many populations and increase the prevalence of global nutritional insufficiency. In general, humans worldwide derive a majority of these nutrients from plants: 63% of dietary protein comes from vegetal sources, as well as 81% of iron and 68% of zinc[9]. Reducing the nutritional density of many of these sources—probably without a perceptible increase in hunger to motivate change—could increase the prevalence and severity of nutritional deficiency globally. This is particularly concerning as over two billion people are currently estimated to be deficient in one or more nutrients[10].

Previous studies have investigated the impact of eCO_2 on the risk of insufficiency for individual nutrients and have shown a range of negative outcomes for global health, each with the potential to imperil the health of millions of people worldwide[8,11,12]. Despite their advances, these previous studies have been limited by their use of national-level food balance sheets to derive country-specific nutrient supplies without the ability to stratify by age or sex. They have also relied on different sets of assumptions for many variables: population growth, physiological nutritional requirements, future diets, the number of foods modelled and their nutrient content. This variation prevents intercomparison across nutrients, and demands re-analysis by bringing all nutrients up to the common standard of using the highest-quality data available. With this in mind, we have performed a new analysis using a unified set of improved assumptions across all nutrients to examine the collective impact of eCO_2 on global nutritional sufficiency. In addition, we used more detailed age- and sex-specific food supply datasets in each country to gain more precise estimates of the individual demographic impacts for each nutrient across 225 different foods, compared with 98 included in the standard food balance sheets used previously in some of these analyses. Finally, we have also incorporated additional information on local food compositions using several regional tables to better determine the foods actually eaten in each country. With the enhancement and harmonization of datasets and assumptions, we have attempted to provide the most accurate synthesis of the global health burden from eCO_2-related nutrient shifts in crops.

Rise in deficiency under elevated CO_2

Assuming our current trajectory of CO_2 emissions consistent with achieving 550 ppm by roughly 2050, we estimate that an additional 1.9% of the global population could become deficient in zinc, corresponding to 175 million people based on 2050 population projections (Table 1). Additionally, we estimate that 1.3% of the global population (122 million) could become protein deficient. For iron, despite the inability to estimate the size of the newly deficient population under eCO_2, we find that nearly 1.4 billion children under 5 and women of childbearing age (57% of the total population of those groups) will live in regions that we identify as highest risk (that is, greater than 4% loss of dietary iron and suffering from a current anaemia prevalence in excess of 20%). These populations who may become newly deficient are in addition to

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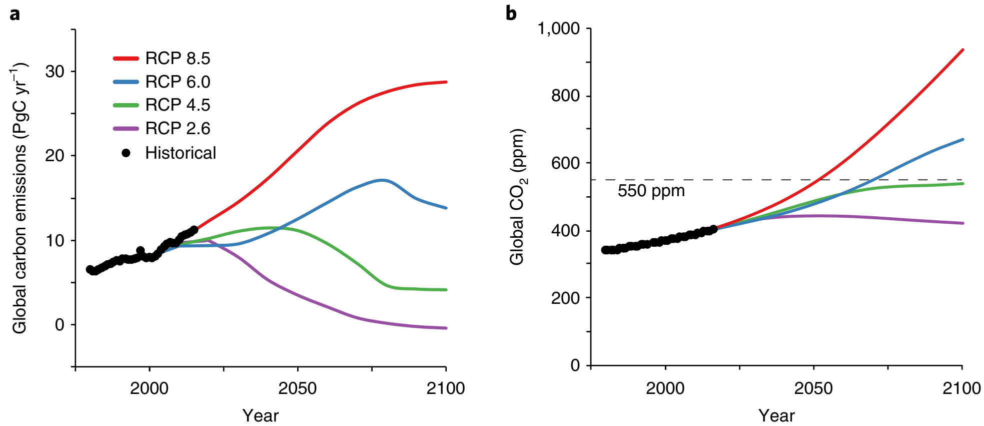

Fig. 1 | Historical trends in CO_2 emissions and atmospheric concentrations compared with model forecasts to 2100. a, Historical CO_2 emissions since 1980 and models of carbon emissions until 2100. The current global level of emissions aligns with the most extreme model forecast (RCP 8.5). **b**, Annual surface global CO_2 concentrations. On the current model trajectory of RCP 8.5, we would attain 550 ppm concentrations by the middle of the century. Under less severe emissions scenarios, we would achieve 550 ppm by later in the century or, potentially, not at all if stringent controls are implemented. RCP projections in **a** and **b** are taken from ref. [3], historical global carbon emission data in **a** are from ref. [5] and historical global CO_2 concentrations in **b** are from ref. [2].

Table 1 | Increase in the nutritionally deficient population in 2050 under eCO_2

Region(s)	Population		Zinc		Protein		Iron	
	Total population (millions), all countries	Total population (millions), countries with GENuS data	Increase in prevalence of zinc deficiency under eCO_2 (%)	Newly zinc deficient under eCO_2 (millions)	Increase in prevalence of protein deficiency under eCO_2 (%)	Newly protein deficient under eCO_2 (millions)	Children (age 0–4) in countries at high risk (millions)	Women (age 15–49) in countries at high risk (millions)
High income	1,073	1,073[a]	0.6 (0.5–0.6)	6.1 (5.4–6.8)	0.4 (0.3–0.6)	4.6 (2.7–7.0)	0	0
Southern and tropical Latin America	328	328	0.8 (0.7–0.9)	2.7 (2.4–3.0)	0.6 (0.3–0.9)	1.8 (1.0–3.0)	0	0
Central and Andean Latin America and Caribbean	456	451[b]	2.2 (2.0–2.4)	9.8 (8.9–10.8)	0.8 (0.5–1.1)	3.4 (2.2–5.0)	2.3	7.2
Central and Eastern Europe	278	278	1 (0.9–1.1)	2.8 (2.5–3.1)	0.8 (0.5–1.3)	2.3 (1.3–3.6)	1.1	4.1
Central Asia, North Africa and Middle East	839	829[c]	2.7 (2.5–2.9)	22.5 (20.5–24.2)	1.2 (0.8–1.7)	10.3 (6.8–14.2)	56.2	179.2
Sub-Saharan Africa	2,203	1,937[d]	1.7 (1.6–1.9)	33.6 (30.9–36.3)	0.8 (0.6–1.1)	16 (11.2–20.7)	26.8	69.6
South Asia (excluding India)	605	604[e]	2.2 (2.0–2.3)	13.1 (12.0–14.1)	1.8 (1.1–2.5)	10.8 (6.8–14.9)	38.9	133.3
India	1,705	1,705	2.9 (2.6–3.2)	49.6 (44.7–53.8)	2.2 (1.5–3.1)	38.2 (26.1–53.0)	106.1	396.0
East and Southeast Asia and Pacific (excluding China)	872	837[f]	1.9 (1.8–2.1)	16.2 (15.0–17.3)	1.5 (0.8–2.1)	12.3 (7.0–17.6)	23.0	84.3
China	1,357	1,348[g]	1.4 (1.1–1.6)	18.3 (15.4–21.6)	1.6 (1.1–2.2)	22.1 (15.5–29.6)	59.4[h]	231.9
Global	9,716	9,391	1.9 (1.7–2.0)	175 (162.2–186.3)	1.3 (1.0–1.7)	121.8 (90.0–157.0)	311.3	1,095.6

Values in parenthesis are 95% uncertainty intervals. [a]Excludes Singapore and the Channel Islands. [b]Excludes Aruba, Curaçao, Martinique, Guadeloupe, French Guiana, Puerto Rico and the US Virgin Islands. [c]Excludes Bahrain, Oman and Qatar. [d]Excludes Burundi, Comoros, Democratic Republic of the Congo, Equatorial Guinea, Eritrea, Mayotte, Réunion, Seychelles, South Sudan and Western Sahara. [e]Excludes Bhutan. [f]Excludes Guam, Micronesia, Papua New Guinea, Taiwan and Tonga. [g]Excludes Hong Kong and Macao. [h]The prevalence of anaemia among Chinese children under 5 is 19%; included in the high-risk category.

the 662 million people we estimate to be currently deficient in protein and 1.5 billion we estimate to be deficient in zinc, and it is believed that up to 2 billion people are iron deficient worldwide (Table 2)[13]. Although not directly quantified here, the exacerbation of existing nutritional deficiencies could create a considerable additional health burden, potentially even larger than those associated with people being pushed into the new onset of these deficiencies.

Table 2 | Scope of current deficiency and exposure to the risks of eCO_2

	Protein	Iron	Zinc
Population with inadequate nutrient intake, billions	0.7	2.0[a]	1.5
Percentage of global nutrients derived from crops that are affected by eCO_2[b]	56	63	57

[a]Estimated from Zimmermann and Hurrell[13]. [b]Individual crops and crop categories with significant loss of nutrition resulting from eCO_2 (described in Supplementary Table 3).

The combined geographic impact across the three nutrients is concentrated in some of the poorest regions globally: India, other parts of South Asia, Sub-Saharan Africa, North Africa and the Middle East, and Southeast Asia. India alone is the largest contributor to all 3 nutritional vulnerabilities: 50 million additional people to the newly zinc-deficient population, 38 million newly protein deficient, and 502 million women of childbearing age and children under 5 who are vulnerable to disease resulting from increasing iron deficiency.

The geographic distribution of eCO_2-related risk is shown in more detail in Fig. 2. For each nutrient, countries were divided into four categories of risk (as shown in Fig. 2b–d), assigned a score between zero and three, then summed to arrive at a combined risk score across all three nutrients (Fig. 2a). The regions with several countries at the highest risk (a combined score equal to or greater than seven) are: India, China, the Middle East, Africa and Southeast Asia. These areas share a high reliance on eCO_2-affected grains (for example, wheat and rice) and legumes for their supplies of major micronutrients, as well as a low intake of animal-sourced foods. Meanwhile, many countries in North America, South America and Western Europe that consume diets heavy in animal-sourced foods have a lower risk, as do countries in Central and Western Africa that are more nutritionally reliant on grains that exhibit little or no nutritional response under eCO_2 (for example, maize, millet and sorghum).

The effect of eCO_2 on the global nutrient supply—particularly in high-risk countries in South Asia and the Middle East—has the potential to significantly increase the health burden related to nutritional deficiencies. The combined annual disability-adjusted life-years lost that are attributed to zinc and iron deficiencies are roughly 58 million, accounting for 5.7% of the global total in 2015[14]. The health impact of protein deficiency is unknown, as it is not typically calculated separately from protein-energy malnutrition, although combined protein-energy malnutrition is responsible for an additional 1.7% of the total 2015 disability-adjusted life-years.

Combined deficiencies across multiple nutrients

Here, we have explored the risk of new nutritional deficiency due to eCO_2 from each nutrient independently, but we are unable to estimate whether the newly affected groups in each country will be distinct or overlapping without knowing individual-level dietary patterns. If overlap was high, the health effects of eCO_2-related nutrient deficiency would be more severe and fall on a smaller population, yet intervention efforts could be more efficient and focused. Despite our inability to directly quantify the overlap in vulnerable groups, there is evidence to suggest that the populations are more likely to be overlapping than separate. In Fig. 3, we show that the nutrient densities of most plant-sourced foods are highly correlated, suggesting that a person who eats mainly vegetal foods, and is on the cusp of nutritional deficiency in one nutrient, is likely to be similarly precarious in all three. However, this does not necessarily hold for animal-sourced foods (Fig. 3b), which have a higher diversity of nutritional densities across nutrients.

Nutritionally vulnerable poor populations tend to have a larger share of their diet composed of vegetal foods, which would expose them to a greater likelihood of combined deficiency across all three nutrients. To investigate this explicitly, we used the World Bank's Global Consumption Database[15] to examine the diets of the 33 countries we found to be at highest risk in Fig. 2a (risk score ≥ 7) and how dietary patterns within these countries are controlled by income. Here, we show that not only does overall food consumption rise with income, but so too does the relative share of animal-sourced foods in the diet (Fig. 4). This would suggest that the

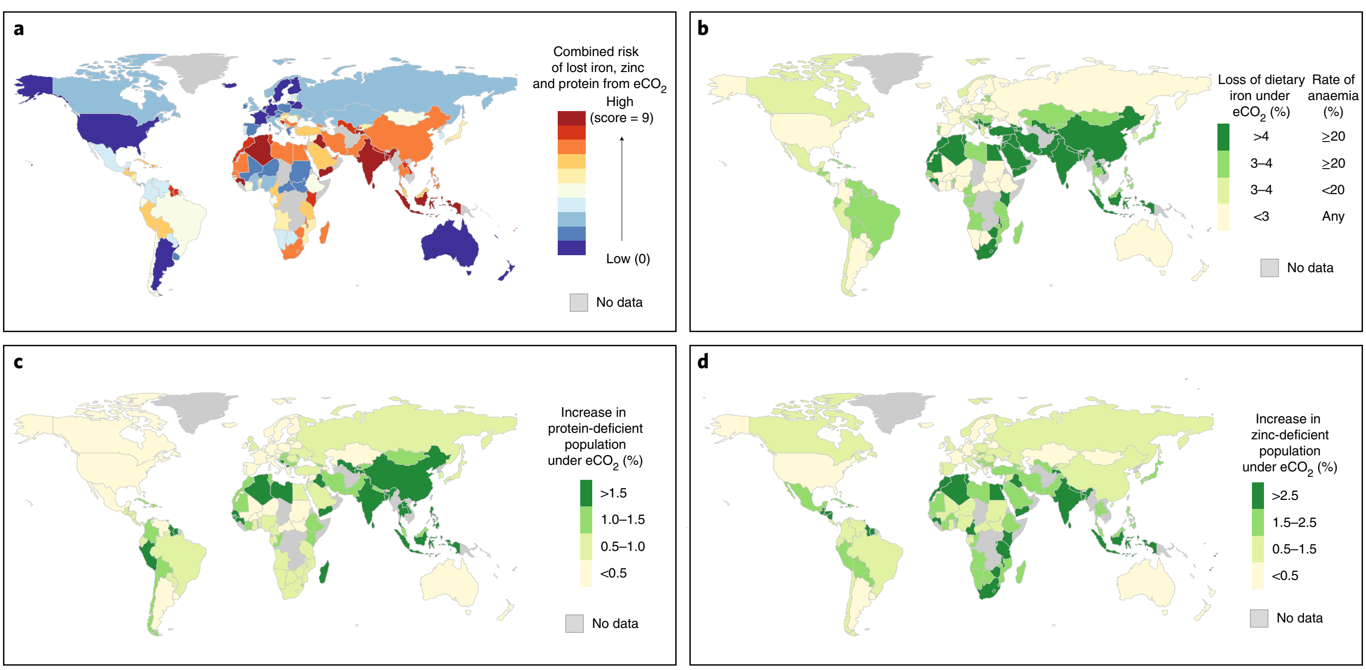

Fig. 2 | Risk of inadequate nutrient intake from elevated atmospheric CO_2 concentrations of 550 ppm. a–d, Combined qualitative summed risk from all nutrients (**a**), and individually for iron (**b**), protein (**c**) and zinc (**d**).

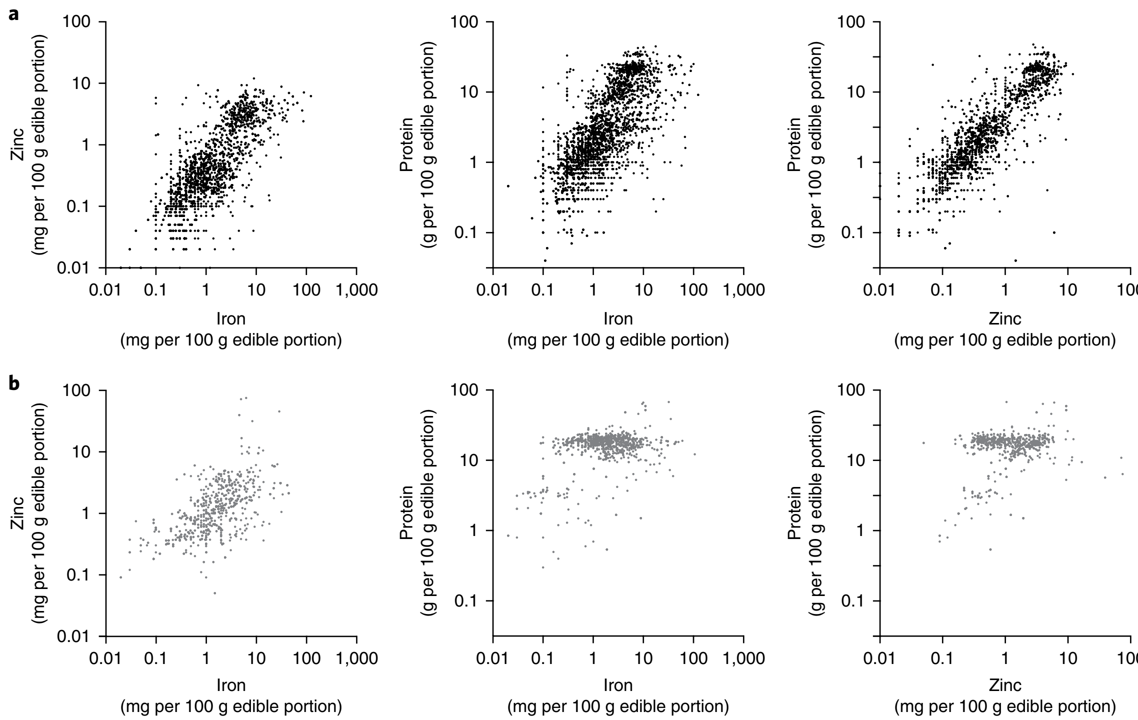

Fig. 3 | Correlations between iron, zinc and protein density of plant- and animal-sourced foods. a, Plant-sourced foods. **b**, Animal-sourced foods. The nutrient density of vegetal foods is well correlated between the three nutrients, but this is not the case for animal-sourced foods. For populations consuming a predominantly vegetarian diet, it is likely that the effect of eCO_2 could cause deficiency across all three nutrients. Nutrient density data were collected from six regional food composition tables representing the global diversity of food intake[24].

lowest- and low-income populations in these high-risk countries are eating a relatively small amount of animal-sourced foods, creating high vulnerability across all three nutrients.

Continued vigilance in an uncertain future

The diets and health of populations globally are changing rapidly, and these trends could either countervail or exacerbate the effects of eCO_2 on diets. The world has predominantly seen improvements in nutrition over the past two decades, particularly in developing countries: the number of underweight people has declined dramatically[16], the prevalence of iron-deficiency anaemia is falling steadily[17] and zinc inadequacy has been reduced in many countries, most dramatically in China[18]. However, these gains have been uneven, and some regions that we identify as the highest-risk areas for eCO_2-related malnutrition have seen limited progress. In particular, India has shown inconsistent gains in addressing undernutrition and nutritional deficiencies. Despite significant progress in reducing the rate of underweight children since 1990, Indian children still have the fourth worst global weight-for-age scores (the standard measure for underweight), and nearly 35% of Indian children continue to meet the criteria for being underweight, far above the developing country average of 20%[16]. Meanwhile, India has seen significant progress in reducing the burden of anaemia, decreasing the number of years lost to disability from anaemia by 28% between 1990 and 2015[14]. However, the prevalence of inadequate zinc intake has increased over much of that same timeframe from 28 to 31% between 1990 and 2005[18]. In contrast, China actively targeted improvements in child nutrition over the same period, reducing its undernourished rate from 24 to 9% between 1991 and 2015[19]. It also decreased its years lost to disability caused by anaemia by 30% between 1990 and 2015, and reduced its rate of inadequate zinc intake from 17 to 8% between 1990 and 2005. In contrast, Sub-Saharan Africa has seen stagnant and even worsening health on some fronts, with the number of undernourished children actually increasing over the past two decades, in contrast with the rest of the developing world[16]. Furthermore, there has been virtually no progress in reducing anaemia and zinc deficiency, even as much of the developing world has seen modest-to-large improvements[17,18]. Countries that are seeing significantly improved nutrition due to shifting diets and increasing incomes may be able to partially offset some of the effects of eCO_2 on nutrition status. However, for those whose progress towards better public nutrition has stalled—including parts of Africa, Oceania and, for certain nutrients, South Asia—extra vigilance may be required.

Our study comes with two caveats. The first is related to our assumption that diets remain static into the future. Modelling of future diets is subject to much uncertainty, hinging on the intersection of future economic and demographic trends, as well as the larger unknowns of the effects of climate change on both future economic development and the availability and distribution of food globally. While pure traditional economic models tend to project past trends of increasing wealth forwards globally, resulting in improved diets, the more uncertain role of climate change, coupled with growing scarcities of fresh water and arable land, could wipe out those gains or worsen diets in many vulnerable regions of the world[20]. Because of this, we hold diets constant not as a prediction of the future, but as a simple, transparent assumption in the face of great model unpredictability, and as a way of providing the most direct estimate of the impact of anthropogenic CO_2 emissions on global nutritional sufficiency independent of dietary changes.

Our second limitation is isolating the effects of rising CO_2 levels on the nutrient density of crops without simultaneously assessing its effect on increasing overall crop yields, often referred to as CO_2 fertilization[21]. However, we chose not to include this effect in this analysis for two reasons. The first is that while eCO_2 may provide a modest fertilization effect, any yield improvements are, on average,

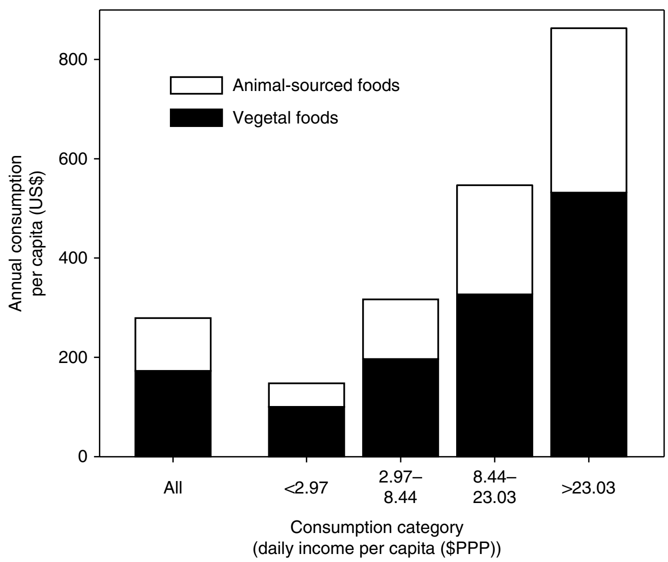

Fig. 4 | Consumption of animal and vegetal foods by income category for the highest-risk countries. Within the 33 countries at highest risk of combined deficiency due to eCO_2 (risk score ≥7 in Fig. 2a), poorer populations have lower food consumption overall, and a smaller share constituted by animal-sourced foods. $PPP represents international dollars adjusted for purchasing power parity, which harmonizes the consumption categories of each country based on its ability to purchase a similar basket of goods using the local currency. US$ are used for per capita consumption to represent a comparable unit of food purchase.

expected to be more than offset by climate change and associated changes in temperature, soil moisture and extreme weather events. The second reason is that even if a particular population were able to increase the total intake of food crops to offset other nutrient reductions, the change in the ratios of nutrients to calories means that individuals would need to overconsume calories to maintain the same nutrient intake, exchanging the problem of nutrient insufficiency for that of obesity and other metabolic diseases.

Despite this study's focus on the rise in new nutritional deficiency caused by rising CO_2, there are already billions of people worldwide who are currently deficient in one or several of these nutrients who are likely to experience exacerbations of these deficiencies. Being nutritionally deficient or sufficient is not a binary biological state, and the health burden of a mild deficiency becoming worse may be more severe than moving from sufficiency to mild deficiency. This is most clearly demonstrated by anaemia, where the moderately and severely anaemic make up a disproportionate proportion of the health burden; although only constituting 39% of the global anaemia prevalence, they together account for 92% of anaemia-related years lived with disability (a measure of morbidity attributable to a disease)[17]. Although we have not directly quantified the health burden of worsening deficiency, it quite clearly has the potential to be an equally severe outcome affecting even larger numbers of people.

Regardless, the aim of this study was not to predict the precise future health burden related to eCO_2. Macroeconomic trends, environmental changes and the potential for adaptation make forecasting speculative. Instead, our goal was to bring focus to what appears to be a significant threat to global nutrition and to highlight those countries that, because of their diet and current health status, should remain careful in monitoring their vulnerability to these effects. This may include active tracking of dietary change over the ensuing decades, but also rigorous and frequent measurement of nutrient levels of eCO_2-affected crops and the secular trends in the rate of nutritional deficiencies within each country.

Beyond stepping up nutritional surveillance, there are a variety of actions that could be taken to reduce nutritional vulnerability. Different cultivars of certain food crops—particularly rice and legumes—have shown differential sensitivity to CO_2 for specific nutrients[7], showing that it may be possible to selectively use or potentially breed cultivars with reduced sensitivity to these effects. In addition, biofortification of crops with nutrients and the use of developing agricultural techniques that optimize the uptake of iron, zinc or nitrogen may be possible and have shown some early promise[22]. Also, national fortification and supplementation programmes may ameliorate nutritional deficiencies, particularly for targeted vulnerable groups[23]. Finally, encouraging dietary diversity through the consumption of greater quantities of nutrient-rich grains and pulses, or even through relatively small increases in animal-sourced foods for developing countries where intake is low and it would be culturally appropriate, may offset nutritional inadequacy with relatively little government intervention. Another clear and direct intervention globally would be to redouble efforts to reduce global CO_2 emissions.

In summary, we find that many people around the world rely on vegetal sources for nutrients that are critical to their health and are likely to suffer nutritional insufficiency in the coming decades as those food crops become nutritionally impoverished as a result of anthropogenic CO_2 emissions. The highest-risk areas—mainly South and East Asia, North Africa, the Middle East, eastern and southern Africa, and Southeast Asia—should continue to actively monitor the nutritional sufficiency of their populations to forestall potential adverse public health outcomes. In the face of continuing anthropogenic CO_2 emissions, these and many other steps will be necessary to sustain the global progress towards improving planetary health.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0253-3.

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Author contributions

M.R.S. contributed to the study design, data acquisition, review and interpretation of the results, execution of the analysis and writing of the manuscript. S.S.M. contributed to the study design, review and interpretation of the results, and editing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Nutrient supply data by country. Nutrient supplies for iron and protein were estimated by country and by age or sex group (five-year bins) for 2011 using Global Expanded Nutrient Supply (GENuS) model datasets. The derivation of the GENuS dataset has previously been described[9] and the datasets are publicly available[25]. We also followed the methodology of Medek et al.[8] and adjusted each food's protein content for digestibility based on food type: plant-sourced protein was assumed to be 80% digestible, whereas animal-sourced protein is 95% digestible[26].

To determine the supply of bioavailable dietary zinc, we assembled an additional database on the phytate content of foods, because dietary phytate—an inhibitor to zinc absorption—was not included in the original version of GENuS. Bioavailable zinc is mathematically related to dietary zinc and dietary phytate using the Miller equation[27,28]. A composite food composition table was constructed using an array of data sources that measured both the zinc and phytate contents of foods (Supplementary Table 1). The default table used was one previously constructed by Wessells et al.[29], supplemented with data from several food composition tables: Bangladesh[30], Gambia[31], India[32] and Tanzania[33]. For foods without data in any of the aforementioned tables, we used additional phytate data from Schlemmer et al.[34] paired with GENuS zinc data, or solely zinc data from the original GENuS dataset for animal-sourced foods that do not contain phytate. The remaining foods that did not have data and were of minor nutritional relevance were omitted from further analysis.

We then accounted for the effect of processing and fermenting on each food's zinc and phytate content. Regional estimates of the percentage processed and nutritional impact of processing were taken from Wessells et al.[29] and applied to estimates of the per-capita food and nutrient supply. GENuS methodology was used to estimate dietary phytate and zinc from the edible food supply, as well as associated uncertainties[9].

Intra-individual distributions of nutrient intake. To estimate the intra-individual variability in nutrient intakes, for zinc we assumed a normal distribution and a 25% coefficient of variation relative to the mean, concordant with previous studies[11,18]. For protein, we assumed a log-normal distribution, with the coefficient of variation for each distribution correlated to the Gini index of income inequality in each country, consistent with previous studies[8]. Projections of future Gini coefficients were not available, so present-day Gini indices (2009–2013 World Bank average[35]) were used, supplemented with data from Milanovic[36] in the absence of World Bank data. The average protein intake for each age and sex group ($\bar{x}$) and the Gini-derived coefficient of variation for each country were used to build a log-normal distribution with the corresponding parameters:[8]

Mean (μ):

$$\mu = \ln \bar{x} - \frac{\sigma^2}{2} \tag{1}$$

Standard deviation (σ):

$$\sigma = \sqrt{\ln(1 + \mathrm{CV}^2)} \tag{2}$$

where CV is the coefficient of variation. For iron, no distribution was estimated because we felt unable to calculate the current or projected rates of deficiency under elevated CO_2 with our current data. Ascertaining the prevalence of iron deficiency requires detailed individual-level data on food and nutrient intake because of the complex interactions between iron absorption and within-meal intakes of other nutrients (for example, ascorbic acid, calcium and polyphenols). Furthermore, iron absorption is also controlled more strongly by the external effects of concurrent disease and iron status, which are unknown in most of the populations studied. Therefore, we limited our analysis to identifying the absolute rates of loss of iron from the diet under eCO_2.

Physiological nutritional requirements. Physiological requirements by age and sex for absorbable zinc were estimated by the International Zinc Nutrition Consultative Group[37] and aggregated to the national level using population data from the United Nations World Population Prospects in 2110[38]. To account for the amount of additional zinc required for pregnant and lactating women per age group in each country, we used the age-specific fertility rates (also from the UN) multiplied by the fraction of each year occupied by pregnancy: 40 weeks. To estimate the number of lactating women by country, the age-specific fertility rate was multiplied by the average duration of lactation, which was assembled for each country from reports provided by the World Health Organization's Global Data Bank on Infant and Young Child Feeding[39] and the World Breastfeeding Trends Initiative[40]. Countries without data were interpolated using regional averages.

For protein, unlike zinc, physiological requirements are derived as a function of weight rather than simply by age and sex. There is no commonly accepted standard for acceptable weight to determine protein deficiency; therefore, we used the World Health Organization (WHO) recommendation of a body mass index (BMI) of 18.5 to be the lowest acceptable normal weight-for-height, below which adults are deemed underweight. We used data from the Non-Communicable Diseases Risk Factor Collaboration group on adult height by age, sex and country[41] to calculate the corresponding weights of each adult demographic group. For children over the age of five and adolescents, WHO BMI-for-age curves[42] were used to calculate the equivalent BMI corresponding to an adult BMI of 18.5. Similarly, WHO height-for-age curves were used to estimate corresponding heights for children and adolescents in each country based on adult heights. For children under five where BMI data were unavailable, the fiftieth percentile weight was used for each country to determine deficiency. The additional protein requirements for pregnant and lactating women were determined as for zinc.

CO_2 effect on the nutrient content of crops. Data on the response of the zinc and iron content of crops to 550 ppm CO_2 were taken from an analysis by Myers et al.[7] using several unpublished datasets to analyse the response of crops under field free-air carbon enrichment experimental set-ups. Protein response data were taken from a meta-analysis by Medek et al.[8]. Response data for broader phylogenetic groupings based on photosynthetic pathways (for example, C_3 grasses and C_3 legumes) were reported by refs [8,11,12]. These groupings are described in Supplementary Table 2. Data on the nutritional responses to eCO_2 for each food and broader groupings, as well as data sources, are provided in Supplementary Table 3.

Risk of additional deficiency under higher CO_2 levels. To estimate the rate of zinc and protein insufficiency, we compared current estimates of the percentage of a population likely to fall below sufficient intake under ambient CO_2 conditions with a scenario in the future where CO_2 concentrations have reached 550 ppm. In this future scenario, we assumed no change in diets or caloric intake. The difference between the two values, multiplied by the population size in 2050 for each age and sex group[38], is reported as the impact of eCO_2 on the rate of deficiency.

Treatment of uncertainty. Several input datasets come with their own associated uncertainties: the nutrient density of crops, food intake by age and sex group, and each crop's response to elevated CO_2. For each variable, the mean and associated uncertainty distributions were included in Monte Carlo simulations ($n = 1{,}000$) to propagate uncertainties and establish uncertainty intervals in our output products. For each iteration, paired model runs of each input variable were run with and without the effect of CO_2, and the difference between them was recorded as the incremental CO_2-attributable effect on deficiency. Afterwards, the middle 95% of model runs were reported as the uncertainty interval (as shown in Table 1).

Data availability. Edible food supply and nutrient totals for iron and protein by country, age and sex can be found in the Harvard Dataverse data repository[25]. Nutrient contents for zinc and phytate can be found in Supplementary Table 1. Crop response to eCO_2 and crop groupings are found in Supplementary Tables 2 and 3.

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