Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study

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Summary

Background Increasing concentrations of atmospheric carbon dioxide (CO₂) lower the content of zinc and other nutrients in important food crops. Zinc deficiency is currently responsible for large burdens of disease globally, and the populations who are at highest risk of zinc deficiency also receive most of their dietary zinc from crops. By modelling dietary intake of bioavailable zinc for the populations of 188 countries under both an ambient CO₂ and elevated CO₂ scenario, we sought to estimate the effect of anthropogenic CO₂ emissions on the global risk of zinc deficiency.

Methods We estimated per capita per day bioavailable intake of zinc for the populations of 188 countries at ambient CO₂ concentrations (375–384 ppm) using food balance sheet data for 2003–07 from the Food and Agriculture Organization. We then used previously published data from free air CO₂ enrichment and open-top chamber experiments to model zinc intake at elevated CO₂ concentrations (550 ppm, which is the concentration expected by 2050). Estimates developed by the International Zinc Nutrition Consultative Group were used for country-specific theoretical mean daily per-capita physiological requirements for zinc. Finally, we used these data on zinc bioavailability and population-weighted estimated average zinc requirements to estimate the risk of inadequate zinc intake among the populations of the different nations under the two scenarios (ambient and elevated CO₂). The difference between the population at risk at elevated and ambient CO₂ concentrations (ie, population at new risk of zinc deficiency) was our measure of impact.

Findings The total number of people estimated to be placed at new risk of zinc deficiency by 2050 was 138 million (95% CI 120–156). The people likely to be most affected live in Africa and South Asia, with nearly 48 million (32–63) residing in India alone. Global maps of increased risk show significant heterogeneity.

Interpretation Our results indicate that one heretofore unquantified human health effect associated with anthropogenic CO₂ emissions will be a significant increase in the human population at risk of zinc deficiency. Our country-specific findings can be used to help guide interventions aimed at reducing this vulnerability.

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Research in context

Evidence before this study
Before this study, there was strong evidence that zinc deficiency was a significant global health problem affecting at least 17% of the global population and responsible for large burdens of disease around the world. More recently, strong evidence has emerged from free air carbon dioxide enrichment (FACE) experiments that the edible portions of food crops grown at elevated atmospheric carbon dioxide concentrations [CO₂] have lower zinc, iron, and protein contents than identical cultivars of the same crops grown under identical growing conditions at ambient [CO₂]. These same experiments showed that phytate concentrations were lower in wheat cultivars grown at elevated [CO₂] but phytate content in other food crops was unaffected.

Added value of this study
This is the first study to combine data on nutrient changes in food crops expected at higher levels of atmospheric CO₂ with estimates of dietary intake of most of the world’s population in order to model the effect of rising [CO₂] on the global risk of zinc deficiency. The study indicates that, in addition to disrupting the global climate system, anthropogenic CO₂ emissions are also threatening millions of people with increased risk of zinc deficiency. The study also indicates that the distribution of the populations at risk of increased zinc deficiency is heterogeneous and concentrated in Africa and South Asia.

Implications of all the available evidence
From a policy perspective, these findings suggest that interventions including biofortification of staple food crops, supplementation, and fortification should be targeted at those populations identified as most vulnerable. In addition, these findings provide additional support for the urgent need to mitigate global CO₂ emissions.

Methods
Effect of elevated [CO₂] on zinc and phytate concentrations
To estimate the size of the effect of elevated [CO₂] on zinc and phytate concentrations, we used a previously published meta-analysis of data pooled by crop, from free air carbon dioxide enrichment (FACE) and open-top chamber experiments in which crops were grown at ambient and elevated [CO₂] and the edible portion of the food crop was tested for zinc, phytate, or both. Phytate concentrations were only found to change significantly in wheat (p<0.05) in response to elevated [CO₂] so only wheat phytate concentrations were adjusted in our scenarios. Estimates of the effect of elevated [CO₂] on nutrient content were used to adjust per-capita nutrient intake from each food commodity as described below.

Country-specific, per-capita zinc and phytate intake
We analysed national food balance sheet data from 2003–07, which are available from the Food and Agriculture Organization, to estimate country-specific, per-capita zinc and phytate intake under both ambient (375–384 ppm during this time period) and elevated (roughly 550 ppm) [CO₂] scenarios. The food balance sheets provide estimated country-specific data for 210 countries or areas on the average daily per-capita consumption of 95 “standardised” food commodities (kcal per capita per day). Of these 210 countries or areas, we could obtain demographic data for 188 countries, which became the subjects of our analysis. The remaining 22 territories and states, mostly small island entities, were excluded from further analyses because we restricted the analyses to national populations. Plant-source food commodities reported in the food balance sheets were initially categorised as C₃ legumes, C₃ tubers, C₄ other plants, or C₄ grasses. If crop-specific data on the effects of elevated [CO₂] on changes in the zinc and phytate contents were available from FACE or open-top chamber experiments, commodities were subsequently assigned to these “primary” groups: maize, peas, rice, sorghum, soya, wheat, barley, and potatoes. When crop-specific data were not available, commodities were assigned to one of three “composite” groups, which were composed of the weighted means of crop-specific data from the FACE or open-top chamber experiments (C₃ plants: wheat and barley, with and without rice; C₄ legumes: soya and peas; C₄ grasses: corn and sorghum). Tubers other than potatoes were assumed to be closest to potatoes and the values for potatoes were used for those crops. Because rice is grown under very different (immersion) conditions than other C₄ plants, it was not clear whether it should be included in our composite estimates of the mean effect of elevated [CO₂] on C₄ plants. To address this uncertainty, we generated two different models for adjusting zinc and phytate contents of the food balance sheet food commodities—one which included rice in the C₄ plant composite estimates and one which did not. The assignment of each food commodity is listed in the appendix (p 1).

The food balance sheet country-specific data on food availability (kcal per capita per day) were used to calculate the per-capita zinc and phytate contents of the daily food supply (mg per capita per day), prior to accounting for the effects of elevated [CO₂]. The estimated zinc and phytate content (mg/100 kcal) for each food commodity at ambient [CO₂] was obtained from a composite nutrient composition database created specifically for the analysis of the zinc and phytate content of national food supplies as reported. Mean estimated zinc and phytate content (mg/100 kcal) for each food commodity was calculated, adjusting for the effects of food processing methods (eg,
decortication, milling, fermentation, and nixtamalisation), according to previous regional assumptions. The mean per-capita zinc and phytate intakes for each country were calculated as the sum of the zinc and phytate contribution from each food commodity. To model physiological zinc intake at elevated [CO2], we used Monte Carlo simulations from each food commodity. To model physiological zinc calculated as the sum of the zinc and phytate contribution per-capita zinc and phytate intakes for each country were under both ambient and elevated [CO2] scenarios were zinc content of the daily food supply for each country and discussion.

Instead of “risk of inadequate zinc intake” in our results risk of inadequate zinc intake based on food balance sheet analysis as a proxy for risk of zinc deficiency, and, for clarity, we use the term “risk of zinc deficiency” instead of “risk of inadequate zinc intake” in our results and discussion.

The fractional absorption of zinc and the absorbable zinc content of the daily food supply for each country under both ambient and elevated [CO2] scenarios were predicted using a saturation response model of zinc absorption as a function of dietary zinc and phytate (the Miller equation). The age and sex distribution of country populations estimated by the 2010 revision of the World Population Prospects were used to calculate the country-specific theoretical mean daily per-capita physiological requirement for zinc, as developed by the International Zinc Nutrition Consultative Group. We estimated absorbable zinc content of the national food supply by dividing the estimated zinc available in the national food supply by the calculated national physiological requirement. We then applied an estimated average requirement cut-point-based method to estimate the proportion of national populations at risk of inadequate zinc intake, assuming a normal population distribution with a 25% interindividual variation, as has been done in previous analyses of global risk of zinc deficiency. Variation in dietary zinc requirements takes into account both variation in requirements for absorbed zinc (ie, variations in metabolism and rate of zinc turnover) as well as variation in the fractional absorption of zinc. We took the difference between the population at risk at elevated [CO2] and the population at risk under ambient [CO2] as our measure of impact.

Population at risk of zinc deficiency

We estimated the prevalence of inadequate zinc intake under each scenario by comparing the estimated absorbable zinc content of the national food supply, as above, with the population’s estimated physiological requirements for absorbed zinc. Detailed methodological and model assumptions, as well as results based on original data, have been described previously. We took risk of inadequate zinc intake based on food balance sheet analysis as a proxy for risk of zinc deficiency, and, for clarity, we use the term “risk of zinc deficiency” instead of “risk of inadequate zinc intake” in our results and discussion.

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Statistical analysis

Regional classifications are based on the reporting regions of the Global Burden of Diseases, Injuries, and Risk Factors 2010 Study with the exception that we broke out India and China separately because of their large population sizes. Regional and global data were weighted by national population sizes. All statistical analyses were completed using SAS System for Windows release 9.3 (SAS Institute, Cary, NC, USA) and the R statistical package V 3.0. Data are presented as means (95% CI), unless otherwise noted.

Role of the funding source

The funders had no role in the study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to the data and final responsibility for the decision to submit for publication.

Results

In a previously published meta-analysis, we found that, when grown under open field conditions at a [CO2] the world is expected to experience by 2050 (roughly 550 ppm), wheat (–9.1%), rice (–3.1%), barley (–13.6%), soya (–5.0%), and field peas (–6.8%) have significantly reduced zinc content. At 550 ppm CO2, estimated per-capita zinc intake varied from a low of 8 mg/day in sub-Saharan Africa to 13 mg/day in China, whereas estimated phytate intake was lowest in southern and tropical Latin America and more than twice as high in Central Asia, North Africa, and the Middle East (table).

The choice of estimates of the physiological requirements for zinc intake has very large implications for the proportion of the global population at risk of zinc deficiency at ambient [CO2] (17% using the International Zinc Nutrition Consultative Group model, table; and 66% using the US Institute of Medicine Food and Nutrition Board model, appendix p 2). However, the estimated effect of elevated [CO2] on global risk of zinc deficiency using these two models varied much less. The total number of people estimated to be placed at new risk of zinc deficiency by 2050 was 138 million (95% CI 120–156) with the International Zinc Nutrition Consultative Group model (table) and 180 million (164–196) with the US Institute of Medicine model.
(appendix p 2). Both models estimated the absolute increase in the proportion of the global population at risk under elevated [CO₂] as 2–3%. We found that populations in Africa and parts of Asia are likely to be most affected (figure 1), with increased risk in sub-Saharan Africa, South Asia, and India of 3·9% (3·0–4·8), 2·9% (2·2–3·6), and 4·2% (2·8–5·6), respectively (table). We found the population of India particularly vulnerable to the impact of elevated [CO₂]. Zinc deficiency has been consistently shown to be associated with compromised immunity function and increased susceptibility to morbidity and mortality from infectious diseases.6,22

Discussion

The global [CO₂] in the atmosphere is expected to reach 550 ppm in the next 40–60 years, even if further actions are taken to decrease emissions.33 These concentrations of CO₂ have been shown to reduce the nutritional value of important food crops,34 and here we show that such nutrient reductions threaten an additional 138 million people estimated to be newly at risk of zinc deficiency globally (appendix p 3) compared to the food availability is the same as in 2010, but the diet is likely to change over the coming decades is thought to be that which did not include rice in the C₃ weighted composite index for C₃ grains did not have a large effect on our results. The “best-estimate” model was considered to be that which did not include rice in the C₃ weighted composite index. We estimated 133 million (115–150) people at new risk of zinc deficiency under elevated [CO₂]. Anticipating how the global risk of zinc deficiency is likely to change over the coming decades while global [CO₂] rises to 550 ppm. We have tried to isolate the CO₂ effect by simply modelling a world in which food availability is the same as in 2010, but the diet is likely to change over the coming decades is thought to be that which did not include rice in the C₃ weighted composite index. We estimated 133 million (115–150) people at new risk of zinc deficiency under elevated [CO₂] as 2–3%. We found that populations in Africa and parts of Asia are likely to be most affected (figure 1), with increased risk in sub-Saharan Africa, South Asia, and India of 3·9% (3·0–4·8), 2·9% (2·2–3·6), and 4·2% (2·8–5·6), respectively (table). We found the population of India particularly vulnerable to the impact of elevated [CO₂]. Zinc deficiency has been consistently shown to be associated with compromised immunity function and increased susceptibility to morbidity and mortality from infectious diseases.6,22

Our analysis does not include the changes in the global diet that will almost certainly take place over the next few decades while global [CO₂] rises to 550 ppm. We have tried to isolate the CO₂ effect by simply modelling a world in which food availability is the same as in 2010, but the diet is likely to change over the coming decades is thought to be that which did not include rice in the C₃ weighted composite index. We estimated 133 million (115–150) people at new risk of zinc deficiency under elevated [CO₂]. Anticipating how the global risk of zinc deficiency is likely to change over the coming decades while global [CO₂] rises to 550 ppm. We have tried to isolate the CO₂ effect by simply modelling a world in which food availability is the same as in 2010, but the diet is likely to change over the coming decades is thought to be that which did not include rice in the C₃ weighted composite index. We estimated 133 million (115–150) people at new risk of zinc deficiency under elevated [CO₂]. Anticipating how the global risk of zinc deficiency is likely to change over the coming decades while global [CO₂] rises to 550 ppm. We have tried to isolate the CO₂ effect by simply modelling a world in which food availability is the same as in 2010, but the diet is likely to change over the coming decades is thought to be that which did not include rice in the C₃ weighted composite index.
increased demand, and the combination of water scarcity, arable land degradation, and climate change represent very significant obstacles to such increases in production. Because of this complexity, we believe the simplest approach is to model diets that are unchanged with respect to calories and composition, an achievement that many would consider optimistic in the face of rapidly changing environmental conditions.

We have also made no attempt to account for population growth in our analysis. The human population is expected to rise to between 9 and 10 billion by 2050, but we have used 2010 estimates of population size for our analysis. This means that our estimates of individuals likely to be placed at risk of zinc deficiency are almost certainly a considerable underestimate. A simple scaling of population growth to the effect we have measured would lead us to conclude that, in fact, 187 million people (using 9.5 billion as an estimate of the 2050 global population) are likely to become newly zinc deficient as a result of increased [CO₂]. And the fact that most of this population growth is expected to occur in the regions that are disproportionately affected by the nutritional consequences of rising [CO₂] suggests that even this number is likely to be an underestimate. However, to maintain the most transparent analysis possible with the fewest assumptions, we have not attempted to project these demographic changes but believe that our results are a conservative estimate.

One assumption we do make for this study is that effects of elevated [CO₂] on crop nutrients that have been quantified in developed country settings for a subset of crops and cultivars consumed globally can be generalised to estimate nutrient intakes around the world. Of course, to be certain of the nutritional effects of elevated [CO₂] on the global population we would need to conduct FACE experiments for every consumed cultivar of every food crop in every country—an undertaking that is not feasible. But we are reassured that having found a very similar pattern of effects across 41 different cultivars of six different food crops grown on three continents in seven locations over 10 years under vastly different growing conditions, that these nutrient changes are a robust finding and are likely to be similar across the different growing conditions around the world. This assumption was also recently supported by a broad meta-analysis showing similar changes in the nutrient content of a diverse number of plants across many plant tissues and many locations.

An additional conservative assumption embedded in this analysis is that food availability in populations around the world is in proportion to physiological requirements. Children younger than 5 years and women (especially during pregnancy) are likely to be at increased risk of zinc deficiency owing to increased nutrient requirements. The assumed optimal distribution of foods is unlikely to be met in most settings, but in the absence of global data on food distributions an assumption must be made, and this assumption is the most conservative approach. Less optimal food distributions would lead to increased effects of elevated [CO₂] on risk of zinc deficiency.

Finally, we have assumed that there is no change in the zinc content of animal source foods. There is clear evidence that most plants, not just food crops, have lower concentrations of zinc when grown at elevated [CO₂]. Meta-analyses of plants that include many different tissues from a variety of grasses, trees, and shrubs show consistent reductions in zinc content, making it likely that animal forage would have reduced zinc content in a world experiencing higher atmospheric [CO₂]. However, there are no data available on how these changes in the nutrient content of forage might alter the concentrations of zinc in animal source foods such as meat, milk, or eggs. Until such data are available, we can only assume no change in nutrient concentrations, but this, too, is likely to lead to underestimates of the impact of rising [CO₂] on risk of zinc deficiency.
The effect we have identified highlights an issue of social justice. Wealthier people are associated with higher CO₂ emissions, whereas the people who are most vulnerable to the nutritional effects of rising CO₂ are those who receive the smallest proportion of their dietary zinc from animal source foods (figure 2). These tend to be the poorest people within a country or region. The wealthy world’s CO₂ emissions are putting the poor in harm’s way.

By modelling national data for 188 countries, we identify populations who are at highest risk of increased zinc deficiency as a consequence of rising CO₂. These populations could be the target of interventions designed to address this risk. Such interventions might include zinc supplementation, fortification of staple foods with additional zinc, the application of zinc-containing fertilisers to crops, and the development and introduction of biofortified crop strains such as rice and wheat. Earlier work has also shown that, at least for rice, different cultivars of a crop show different levels of sensitivity to the [CO₂] effect on zinc content which could provide an opportunity for breeding crop cultivars with lower nutritional sensitivity to rising [CO₂].

Anthropogenic change to Earth’s natural systems will affect human health in multiple ways through pathways that are often quite complex. Here we describe one such pathway that would have been challenging to anticipate in advance of the experimental data. We suspect that there will be others as human transformation of natural systems becomes increasingly profound and pervasive.

Contributors
SSM designed the study. KRW and IK led the data analysis. AZ and JS provided statistical support. All authors contributed to data interpretation and the writing of the article.

Declaration of interests
We declare no competing interests.

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