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Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study

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Contributors

AC and LHZ conceived the study and provided overall guidance. TBS, NC, and DM-D developed the analytical framework and did the modelling. SM and MS prepared the nutrient data and did the analysis. TBS, NC, RHB, JC, and AC did data analyses and developed data tables and manuscript figures. RHB, TBS, AC, and MCS prepared the first draft. All authors contributed to conceptualisation, reviewing results, and reviewing and revising the manuscript.

Declaration of interests

We declare no competing interests.

For the online **GitHub** resource see <https://github.com/IFPRI/Mid-century-eCO2-fx-proteiniron-Zinc>

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Summary

Background—Increasing atmospheric concentrations of carbon dioxide (CO₂) affect global nutrition via effects on agricultural productivity and nutrient content of food crops. We combined these effects with economic projections to estimate net changes in nutrient availability between 2010 and 2050.

Methods—In this modelling study, we used the International Model for Policy Analysis of Agricultural Commodities and Trade to project per capita availability of protein, iron, and zinc in 2050. We used estimated changes in productivity of individual agricultural commodities to model effects on production, trade, prices, and consumption under moderate and high greenhouse gas emission scenarios. Two independent sources of data, which used different methodologies to determine the effect of increased atmospheric CO₂ on different key crops, were combined with the modelled food supply results to estimate future nutrient availability.

Findings—Although technological change, market responses, and the effects of CO₂ fertilisation on yield are projected to increase global availability of dietary protein, iron, and zinc, these increases are moderated by negative effects of climate change affecting productivity and carbon penalties on nutrient content. The carbon nutrient penalty results in decreases in the global availability of dietary protein of 4·1%, iron of 2·8%, and zinc of 2·5% as calculated using one dataset, and decreases in global availability of dietary protein of 2·9%, iron of 3·6%, and zinc of 3·4% using the other dataset. The combined effects of projected increases in atmospheric CO₂ (ie, carbon nutrient penalty, CO₂ fertilisation, and climate effects on productivity) will decrease growth in the global availability of nutrients by 19·5% for protein, 13·6% for iron, and 14·6% for zinc relative to expected technology and market gains by 2050. The many countries that currently have high levels of nutrient deficiency would continue to be disproportionately affected.

Interpretation—This approach is an improvement in estimating future global food security by simultaneously projecting climate change effects on crop productivity and changes in nutrient content under increased concentrations of CO₂, which accounts for a much larger effect on nutrient availability than CO₂ fertilisation. Regardless of the scenario used to project future consumption patterns, the net effect of increasing concentrations of atmospheric CO₂ will slow progress in decreasing global nutrient deficiencies.

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Introduction

Despite substantial decreases in the rate of global undernutrition over the past few decades, a large global burden of disease associated with deficits in intake of protein, iron, zinc, and other nutrients remains.^{1,2} Additionally, progress in decreasing undernutrition has stagnated

or deteriorated in many countries.¹ 25–30% of the global population are deficient in at least one key micronutrient.³ This proportion includes an estimated 10–15% of people who are at risk of insufficient iron intake,⁴ 17% at risk of zinc deficiency,^{5,6} and 12% at risk of protein deficiency.⁷ Increasing population and nutrient demands and the effects of climate change have the potential to exacerbate these threats to global food security.⁸

Chronic dietary deficiencies of micronutrients contribute to so-called hidden hunger, for which the consequences (eg, adverse effects on metabolism, the immune system, cognitive development, and maturation) might not be immediately visible or easily observed.⁹ Children and pregnant women are especially vulnerable to nutritional deficits.¹⁰ Insufficient protein intake, which might coincide with micronutrient deficiencies, restricts growth and tissue repair and results in low birthweight, wasting, stunting, and other health issues that cause approximately 2.2 million annual deaths in children younger than 5 years. Zinc deficiency is estimated to cause approximately 100 000 deaths per year in children younger than 5 years.¹⁰ The global burden of disease associated with iron deficiency has been estimated at nearly 200 000 deaths and 45 million disability-adjusted life-years annually.¹¹

Widely used global economic models of the agricultural sector generally project increasing agricultural production and improved food availability per capita over the next few decades.¹² These models typically focus on the production and consumption of major agricultural commodities and do not directly assess availability of individual nutrients, although increasing food availability per capita implies expectations of progress in achieving decreases in hunger and undernutrition. Springmann and colleagues¹³ used the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to provide detailed projections of food consumption through 2050 and found increasing availability per capita of calories, fruits and vegetables, and red meat in all regions of the world, except for a slight decrease in consumption of red meat in high-income countries.

However, this projected progress towards improved global food security might be slowed or even reversed in some countries because of increasing concentrations of atmospheric greenhouse gases and their associated effects on the climate. Increasing concentrations of greenhouse gases will contribute to climate change that is expected to decrease global crop yields compared with a no-climate-change scenario^{14,15} and result in reduced food supply and increased commodity prices.^{12,16} Although the fertilisation effect of increased concentrations of atmospheric carbon dioxide (CO₂) would tend to increase crop yields if other factors were held constant (ie, the CO₂ fertilisation effect), increased atmospheric concentrations of CO₂ and other greenhouse gases lead to changes in temperature, precipitation patterns, extreme weather events, and other climatic conditions that must be considered simultaneously. Although considerable temporal and spatial variability in the magnitude and direction of effects on agricultural productivity exists, the effects of increasing concentrations of greenhouse gases are generally found to be increasingly negative as the magnitude of climate change increases. Due to concerns about negative effects on yields and food production, climate change has been identified as a substantial threat to future food security.⁸

An often overlooked effect of greenhouse gas emissions is the effect of increased concentrations of CO₂ on the nutrient content of food crops and consequent effects on human nutrition.^{4,6,7,9,17–19} Since first hypothesised in 2002,²⁰ increased concentrations of atmospheric CO₂ in in-situ experiments have been found to decrease the concentrations of key macronutrients and micronutrients in many important food crops.^{17–19} Edible plant tissues have an increase in the concentration of carbon (and potentially other micronutrients that are composed only of carbon, hydrogen, and oxygen, such as vitamin C in fruits and vegetables),^{20,21} but a decrease in all other elements (eg, protein, iron, zinc, magnesium, potassium). The potential effects of increasing concentrations of CO₂ on global prevalence of nutrient deficiencies have been examined for protein (with nitrogen serving as a common proxy),^{7,18,22,23} iron,^{4,19,23,24} and zinc.^{5,6,23,24} Under increased concentrations of atmospheric CO₂, non-leguminous C₃ crop species of plants that do not fix nitrogen increase the synthesis of carbohydrates, decrease protein content, and alter relative proportions of major macronutrients.^{9,17,18,25} Although C₄ plants are expected to be less affected than C₃ plants,^{18,19} most C₃ plants (eg, rice, wheat, potatoes) and some C₄ plants (eg, maize, sugarcane) show decreases in the nutrient content of edible tissues.^{17,23}

The potential impact of climate change on productivity of food crops and increased concentrations of atmospheric CO₂ on nutrient content are typically addressed independently by different scientific disciplines. To our knowledge, this study is the first synthesis of these factors to determine changes in both nutrient content and productivity of key agricultural commodities in 2050 due to climate change, CO₂ fertilisation, and CO₂ nutrient effects. We combine these changes with projections of agricultural yields, prices, income, trade, and consumption to estimate net changes in nutrient availability.

Methods

Study design

In this modelling study, we analysed nutrient availability under several scenarios: first, 2010-climate conditions for CO₂ concentrations and socioeconomic conditions in 2010; second, 2050-climate conditions, in which effects of climate change (eg, temperature, precipitation) and socioeconomic conditions (eg, market forces, technology) are projected to 2050 with CO₂ fertilisation but without any nutrient effects; and finally, two 2050-nutrient scenarios, in which CO₂ nutrient content effects from two datasets, Loladze (2014)¹⁸ and Myers et al (2014),¹⁹ are applied on top of the 2050-climate scenario.

To quantify future pathways of agricultural markets, we applied IMPACT, a global economic model of the agricultural sector.²⁶ This model incorporates changes in production, trade, prices, and consumption of agricultural commodities at global and regional levels, and projects effects on crop yields by crop type for changes in climate resulting from the Representative Concentration Pathway (RCP) scenarios. Next, we used data from the Global Expanded Nutrient Supply (GENUS) model²⁷ to calculate nutrient content per unit of agricultural commodity in each region (appendix p 11), which are then multiplied by our modelled consumption levels to obtain the nutrient availability per capita in each country or region for the 2010-climate and 2050-climate scenarios. To estimate nutrient availability for the 2050-nutrient scenario, we then multiplied the 2050-climate nutrient availabilities by a

so-called carbon nutrient penalty. This penalty was derived from changes in concentration of protein, iron, and zinc at an increased atmospheric concentration of CO₂ of 541 ppm, as projected under RCP8.5 scenario in 2050, from two datasets: Loladze¹⁸ and Myers et al.¹⁹ These datasets were chosen because they reflected independent observations of effects on protein, iron, and zinc across multiple crop types and under varying levels of increased CO₂ conditions. Although these two datasets provide similar information, they reflect data from a different mix of studies, crops, and methods. These steps are outlined in more detail in the following paragraphs. Consistent with many other studies, we also analysed the 2050-climate and 2050-nutrient scenarios under the RCP4.5 scenario and without CO₂ fertilisation to assess the relative importance of the magnitude of climate change and the fertilisation effect (appendix pp 6–8).

Because recommended nutrient intake (RNI) for protein, iron, and zinc differs by country and region, we compared changes in nutrient access with its RNI in that country or region. RNI values by age and sex for both iron and zinc were taken from the joint UN Food and Agriculture Organization (FAO) and WHO recommendations.²⁸ However, dietary requirements for both iron and zinc can vary depending on other aspects of the diet that can inhibit or enhance nutritional absorption by the body (eg, eating meat or fish can enhance iron uptake, whereas consuming tea, coffee, or calcium can inhibit iron absorption). Therefore, we attempted to account for differences in the diet-controlled bioavailability of iron and zinc by sorting countries into one of three bioavailability categories for zinc and one of four categories for iron, similar to a technique used by Golden and colleagues.²⁹ We aggregated age-sex-specific RNIs to population-weighted country averages using UN population data for 2015.³⁰ Protein requirements, unlike iron and zinc requirements, are determined by the weight of the individual rather than simply age and sex, and joint FAO and WHO recommendations for protein requirements are given as g of protein per kg of bodyweight per day.²⁸ We estimated protein RNI values from joint FAO, WHO, and UN University recommendations,³¹ corrected for each country's average bodyweight using a methodology equivalent to that of Medek and colleagues.⁷ More detailed methods on calculating nutrient requirements are in the appendix (p 9).

Changes in agricultural markets

We used the IMPACT model²⁶ to assess the combined effects of increased atmospheric CO₂ and climate change on regional nutrient availability, including market responses to changes in productivity. IMPACT is a partial equilibrium model of the global agricultural sector that has been applied in several previous studies.^{12,13} This model simulates global and national markets for 62 agricultural commodities. The model disaggregates the world into 158 geopolitical regions, either countries or multi-country regions. For synthesis purposes, we present results at higher levels of regional aggregation than simulated by this model. Additional information on the model and its application for this study are in the appendix (pp 2–3). Trends of growth in agricultural productivity are shown by exogenous growth rates for each commodity and country by irrigated and rainfed systems. The set of exogenous productivity growth rates was based on historical trends and expert opinion about future potential for change given associated development trajectories for a particular combination of commodity and country, and were developed in collaboration with scientists across the

Consultative Group on International Agricultural Research Consortium of International Agricultural Research Centers and the Agricultural Model Intercomparison and Improvement Project network. Average growth rates for the world across crops are projected to be about 1% per year until 2050, with increased growth occurring in developing nations and non-cereal crops.²³

Socioeconomic development assumptions interact with IMPACT yield projections to determine agricultural production, commodity prices, trade, and consumption for each country and region modelled. Our projections use the Shared Socio-economic Pathway 2 (SSP2) scenario³² defined in the 5th Intergovernmental Panel on Climate Change Assessment Report. SSP2 is considered an intermediate framework for characterisation of the future, largely continuing current trends. Under these conditions, the world's population reaches 9.2 billion and global average gross domestic product per capita more than doubles by 2050.

We estimated productivity effects for the 2050-climate scenario resulting from climate change between 2010 and 2050 using the IMPACT framework that uses the DSSAT model for five global climate models (GCMs) drawn from the Intersectoral Impact Model Intercomparison Project (ISI-MIP) archive;³³ National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamic Laboratory Earth System Model; Hadley Centre's Global Environment Model, version 2; Institut Pierre Simon Laplace's Earth System Model; Model for Interdisciplinary Research on Climate Earth System Model; and the Norwegian Earth System Model. Additional model descriptions and references are in the appendix (p 2).

We used estimated climate change effects from the RCP8.5 and RCP4.5 scenarios to define our crop productivity scenarios. RCP8.5 corresponds to a scenario with continued high growth in greenhouse gas emissions such that global atmospheric CO₂ concentrations increase from current-day concentrations of approximately 400 ppm to 936 ppm by 2100. By 2081–100, projected warming under the RCP8.5 scenario ranges from 2.6°C to 4.8°C above the 1986–2005 baseline. The projected atmospheric CO₂ concentration under RCP8.5 for 2050 is 541 ppm, with projected warming of 1.7°C above the 1986–2005 baseline. Projected CO₂ concentrations and temperatures in 2050 under RCP8.5 are roughly equivalent to concentrations in 2100 under RCP4.5, in which temperature is projected to increase by 2°C. We simulated each combination of RCP scenario and the five GCMs both with and without CO₂ fertilisation to capture the role of CO₂ fertilisation effects. For the 2050-climate scenario, we modified the yield projections from IMPACT to include percentage changes in yields by crop, region, and time period, consistent with effects on productivity from the ISI-MIP scenarios.

We combined projected changes in per capita food availability with technical coefficients for the nutrient content per kg of each food, as calculated from published GENUS data,²⁷ to determine nutrient availability for the 2050-climate scenario.

Carbon nutrient penalty

For the 2050-nutrient scenarios, we applied a carbon nutrient penalty with changes in nutrient concentration shown as a function of atmospheric CO₂ concentration on the basis of data from both Loladze¹⁸ and Myers et al.¹⁹ We used these two sources separately to determine whether the existing data were mutually reinforced in both direction and magnitude of effects. Although suggesting these two datasets are the high or low ends of a range of effects would be inappropriate, presenting results from both datasets allowed us to assess whether different carbon nutrient penalties for specific crops led to differences at the region or country scale. To determine the carbon nutrient penalty for each dataset and crop type, we applied the following inclusion criteria.

First, we used only data derived from either free-air CO₂ enrichment (FACE) or open-top chambers (OTCs) experiments, with one exception. FACE and OTC data were not available for most vegetables, and yet vegetables are one of the most important sources of global iron and zinc. Hence, we used data from Loladze¹⁸ for an aggregate vegetable category that was derived from experiments other than FACE or OTC combined with FACE and OTC data from spinach and applied this value to all vegetables. Second, we only used data for edible portions of food crops. We then used the following decision protocol to define the carbon nutrient penalty applied to each commodity modelled in IMPACT: when estimated nutrient effect data existed for a given crop with a significance value of $p=0.05$ or lower, we used those values; when the data for a given crop existed but were not significant, we assumed zero effects; and when data for a given crop did not exist, we determined the nutrient effect of that crop with the average nutrient effect for that class of crop. We calculated averages for C₃-legumes, C₃-tubers, and C₃-grasses weighted by the inverse of the variance, or by sample size when variance was not available, for each crop included in the average. When direct measurements for a C₄ crop did not exist, we assumed the effect to be zero. For C₃ crops that did not fall into one of the three group categories, we used the weighted average for all C₃ crops in the case of zinc and iron effects. Because legumes have nitrogen-fixing capabilities and therefore legume proteins could be expected to have a smaller sensitivity to increased atmospheric CO₂ concentrations, for C₃ crops that did not fall into one of the group categories, we used a weighted average of all non-legume C₃ crops for protein effects.

Data analysis

Using these carbon nutrient penalties, we estimated changes in the concentration of protein, iron, and zinc available in major food crops under an increased atmospheric concentration of CO₂ of 541 ppm (consistent with RCP8.5 in 2050) and 487 ppm (consistent with RCP4.5 in 2050) assuming a linear CO₂-nutrient association (figure 1; appendix p 7). These values were multiplied by our simulated food consumption patterns under climate change to examine changes in future nutrient availability under the 2050-nutrient scenarios.

Role of the funding source

The funders supported analysis, interpretation, and writing of the manuscript. All coauthors and individuals listed in the Acknowledgments who reviewed the manuscript had full access to all the data in the study. The corresponding author had final responsibility for the decision

to submit for publication. Findings and decision to submit do not reflect the official position of any funding institutions, including the US Environmental Protection Agency.

Results

For the 2050-climate scenario, we found an increasing per capita availability of protein, iron, and zinc in all regions compared with 2010-climate conditions (table). Because of projected improvements in crop yields and increasing incomes, global per capita availability of protein is projected to increase by 17.6%, of iron by 19.9%, and of zinc by 18.2% by 2050 without including nutrient effects (table). Although nutrient availability still increases when considering nutrient effects, the projected increases are moderated for all nutrients analysed and in all regions compared with the 2050-climate scenario. Application of the carbon nutrient penalty calculated on the basis of the Loladze dataset¹⁸ resulted in decreases in global availability of protein of 4.1%, iron of 2.8%, and zinc of 2.5% from the 2050-climate conditions (table). Application of the carbon nutrient penalty calculated on the basis of the Myers et al dataset,¹⁹ resulted in projected decreases in global availability of protein of 2.9%, iron of 3.6%, and zinc of 3.4% from the 2050-climate scenarios (table). The greater decreases in nutrient availability calculated with climate effects on agricultural productivity and CO₂ effects on nutrient quantity, but without CO₂ fertilisation, might be considered an upper bound on potential effects and are shown in the appendix (p 25).

The results from our model show uniformly negative effects of increasing atmospheric CO₂ on protein, iron, and zinc availability compared with the 2050-climate scenario across all countries and regions of the world, although with substantial differences in the magnitude of these effects (table, figures 2 and 3; RCP4.5 scenario data, RCP8.5 scenario data without CO₂ fertilisation, and the by-country disaggregated data for the graphs are in the appendix [pp 24, 25, 26–29]; all other data are in the online GitHub resource). The effects of increased atmospheric CO₂ on nutrients are largely similar in direction and magnitude across the Loladze and Myers et al 2050-nutrient scenarios. Under the 2050-nutrient scenarios, decreases in availability of protein from the 2050-climate scenario are less severe than the global average decrease in Latin America and the Caribbean, North America, and sub-Saharan Africa, and more severe than the global average decrease in all other regions across both datasets. Decreases in protein availability in the former Soviet Union and Middle East and north Africa regions are especially severe. Decreases in zinc availability are less severe than the global average decrease in Latin America and the Caribbean, south Asia, and sub-Saharan Africa and more severe in Europe, the former Soviet Union, the Middle East and north Africa, and North America regions. Both the Loladze and Myers et al datasets result in less severe decreases in iron availability than the global average decrease in Latin America and the Caribbean and North America regions and more severe decreases in iron availability than the global average decrease in the Middle East and north Africa and sub-Saharan Africa regions. The rest of the regions all show decreases in iron availability but differ across the two datasets as to whether those decreases are more or less severe than the global average decrease. Decreases in availability of protein, iron, and zinc are less severe under RCP4.5 than under RCP8.5 in all regions and follow the same regional pattern compared with global average decreases, like the RCP8.5 projections described previously (appendix p 24).

RNI varies across regions because of differences in nutrient bioavailability from different food sources. In general, people in low-income and middle-income countries receive a larger portion of their nutrients from plant-based sources with lower bioavailability than animal-based sources; thus, their RNI is higher than in countries that rely heavily on animal-based sources for these nutrients. Almost all regions have an average nutrient availability-to-RNI ratio of more than one, both before and after carbon nutrient penalties are considered, although the penalties do decrease this RNI ratio in all regions (figures 2 and 3). Ratios for iron in south Asia are below one for both the 2050-climate and 2050-nutrient scenarios under RCP8.5. For zinc in south Asia, the RNI ratio is greater than one under the 2050-climate scenario, but below this threshold under the 2050-nutrient scenario under both the Loladze and Myers et al datasets.

In a region, country-specific values might vary such that specific countries are closer to or below this ratio of one. For example, although the aggregated sub-Saharan Africa region shows an iron RNI ratio of more than one, 24 of 44 countries or subregions in this region have ratios below one in both the 2050-climate and 2050-nutrient scenarios for both Loladze and Myers et al. Furthermore, two countries in this region, Eritrea and Equatorial Guinea, have iron ratios that are above one in the 2050-climate scenario, but below one when considering carbon nutrient penalties. Similarly, Yemen, Nicaragua, and India all have zinc RNI ratios above one in the 2050-climate scenario but below one in the 2050-nutrient scenario for Loladze and Myers et al datasets. All country-specific RNI ratios are in the appendix (pp 26–29). Notably, even for countries that have an RNI ratio of more than one, considerable variation in terms of individuals within those countries exists. Therefore, the decrease in nutrient availability due to the carbon nutrient penalty could still result in some individuals having new or worsening of existing nutrient deficiencies.

Total impact on nutrient availability on a global level can be attributed to several key factors (figure 4). As with previous studies, we find the largest driver of projected increases in nutrient availability in 2050 compared with 2010-climate conditions across all three nutrients is advances in technology and agricultural market adjustments. Increased productivity due to CO₂ yield fertilisation should lead to additional increased nutrient availability; however, decreases in nutrient content due to increased atmospheric CO₂ more than negate the potential yield fertilisation effects. We found the effects of climate change on nutrient availability via effects on crop productivity are generally negative but small compared with other effects. Notably, the modelled economic feedbacks will generally moderate direct effects on yield, whether beneficial (fertilisation) or negative (climate damages), as the model adapts by shifting resources. However, our model does not adapt to nutrient effects, which are considered to be invisible to the market. When averaging results from both the Loladze and Myers et al datasets, the total effect of increased atmospheric CO₂ (ie, carbon nutrient penalty, CO₂ fertilisation, and climate effects on productivity) decreases the projected growth in global nutrient availability per capita from technology and market changes between 2010 and 2050 by 19.5% for protein (3.11 g per person per day), 13.6% for iron (0.60 mg per person per day), and 14.6% for zinc (0.37 mg per person per day). Some of the largest percentage changes in effect due to increased atmospheric CO₂ occur in regions where agricultural production is already efficient (eg, Europe and North America) and technological improvements in the IMPACT model are thus slower than in

other regions. Regions with larger percentage decreases due to carbon nutrient effects are, in general, more dependent on plant-based sources of protein, iron, and zinc that are most sensitive to increased atmospheric CO₂ than on animal-based sources (figures 2 and 3). For some nutrients in some regions, namely zinc and iron in the Middle East and north Africa and North America, and protein in Europe, the effects of increased atmospheric CO₂ almost negate the combined expected improvements in nutrient availability from agricultural productivity and CO₂ fertilisation effects by 2050.

Some of the largest carbon nutrient effects are observed in the response of wheat in the Loladze dataset and barley in the Myers et al dataset (figure 1). A large portion of barley is used in beer production, although it remains an important food crop in north Africa and regions where wheat is difficult to grow. Wheat is a substantial contributor to diets in many regions, and therefore changes in nutrient concentrations can have substantial effects on dietary micronutrient availability. For example, in the Loladze dataset (appendix p 7) nutrient availability in wheat is projected to change significantly by 2050 in all regions, with a projected carbon nutrient penalty of -11.7% on protein availability, -6.7% on iron availability, and -5.8% on zinc availability. The largest decreases in protein availability occur in the former Soviet Union, the Middle East and north Africa, and countries in the east of Europe, where wheat consumption is particularly high (figure 2). Because micronutrient effects of increased atmospheric CO₂ differ between crops, consideration of the regional patterns of crop consumption (eg, wheat vs rice) is important for estimating the net effect of increasing atmospheric CO₂ on micronutrient availability.

Additional data are available in the appendix and in the GitHub resource.

Discussion

Several environmental and cultural factors influence access to protein, iron, and zinc; however, estimates of the effect of climate change on future consumption in previous studies are based on holding constant current patterns of food consumption or simplistic projections of dietary changes. One of the key strengths of this study is the use of a structural model of the agricultural sector to generate projections of global food availability up to 2050. When combined with projections of agricultural yields, prices, income, and trade, our approach simultaneously captures projections of future dietary patterns, the effect of climate change on crop productivity, and changes in nutrient content under increased atmospheric concentrations of CO₂. This approach provides a more complete picture of global food security in the context of increasing atmospheric CO₂ and climate change. Additionally, although the effects of increasing atmospheric CO₂ on nutrient content are not typically included in studies of effects of climate change on food and agriculture, we found they account for a much larger effect than CO₂ yield fertilisation or the effect on crop productivity from changes in temperature and precipitation due to climate change. This finding implies that the current literature on economic modelling of the effect of climate change on food security is neglecting a potentially important effect on nutrition.

Overall, the net effects of increased atmospheric CO₂ on nutrient content are to decrease per capita availability of protein, iron, and zinc both regionally and globally relative to expected

changes in nutrition in the future when not accounting for carbon nutrient penalties. Although the two data sources we used for the effect of increased atmospheric CO₂ on nutrients in edible plant tissues were developed by use of different methods, they reinforce each other by showing overall effects in the same direction and of similar magnitude. These findings suggest that climate change and increasing CO₂ concentrations are expected to slow the progress of improvements in global nutrition modelled in our scenarios. Disproportionate effects are projected to occur in countries that currently have deficiencies of protein, iron, or zinc, such as the Middle East and north Africa, sub-Saharan Africa, and south Asia. Although the IMPACT model simulations were only projected to 2050, an extension of our analysis to the period between 2050 and 2100, when stronger effects from climate change are expected, would result in larger estimated effects.

Although this analysis quantifies an important factor that will decrease nutrient availability in the future, it does not project the consequence of altered protein, iron, or zinc content on human health or global burden of disease.³⁴ Importantly, a given percentage decrease in nutrient availability translates to different implications for nutrition and health across regions. For example, the same percentage decrease might translate to a greater quantity decrease in nutrient intake in high-income countries (eg, when measured in mg). However, the effect on human health is likely to be larger in low-income and middle-income regions where baseline nutrient levels are lower relative to their RNI than in high-income countries, potentially slowing efforts to ease the burden of disease. In high-income countries, where per capita nutrient intake and bioavailability are high, such decreases in average intake of protein, iron, or zinc might have little effect, at least for most of the population. Decreased consumption of some micronutrients in populations in which intake of these nutrients might currently be too high could even result in positive effects. Additionally, an important aspect to consider is the many factors beyond food consumption that influence nutrition and health outcomes—such as sanitation, incidence of disease, access to potable water, and education, among many other public health factors.

The current approach had several limitations. First, we focused on crops, but climate change is expected to affect livestock (including poultry and fish), the nutritional content and costs of feed for livestock, and thus nutritional effects on humans from any combination of these effects. Second, mapping the crops for which nutrient data are available to the crops included in the IMPACT model led to several instances in which average values were used or specific crop data did not meet our criteria for inclusion (appendix p 4); such gaps could be addressed with further research. Third, assumptions about technological improvements in the IMPACT model are represented as changes in yields, although the development of new crop varieties could potentially alter nutritional composition. Fourth, in addition to long-term equilibrium outcomes, short-term disruptions (eg, extreme events) in food supply can also result in nutrient deficiencies, which are not assessed in this analysis. Fifth, although the IMPACT model reflects adaptation to some extent (adjustments in regional crop mix, production practices, and trade in response to changes in crop yields), additional measures and technologies are available that might mitigate decreases in nutrient availability; further research could assess costs and benefits associated with such strategies. Finally, we present changes in projected nutrient consumption per capita by country or region, but important disparities also exist within diets at smaller scales, with distributional effects at the

household, local, national, or regional level varying by age, sex, culture, location, and socioeconomic status. For example, nutritional effects on children are particularly important for cognitive development and maturation. Even in regions where the average micronutrient availability is above the RNI, many individuals have nutrient deficiencies. Furthermore, people often choose to diversify their diets over time as their socioeconomic status changes.

We expect that the relative effect of increased atmospheric CO₂ would be insensitive to baseline projections of consumption, although different assumptions would change the number of individuals who are nutrient deficient. The choices inherent in the socioeconomic scenario presented in this analysis include several uncertainties—eg, embedded in the SSP2 scenario are assumptions of a general continuation of economic growth over the next several decades, agricultural productivity improvements, and a population growth rate that lies between the UN's median and low population projections.³⁰ These assumptions led to projections of a continued increase in food availability in the IMPACT model, and therefore increased future micronutrient consumption. However, slower economic growth (such as under the SSP3 scenario), limits to technological advances in the agriculture sector, competition from increased use of biofuels, degradation of existing agricultural land or land use changes, loss of biodiversity, threats to water supply, higher population growth, or sociocultural preferences for diets with poor nutrient content could lead to increased adverse outcomes and worsened nutrient inadequacies, particularly in low-income countries.³³ Furthermore, although physical climate effects (eg, changes in temperature and precipitation patterns) under RCP8.5 and RCP4.5 scenarios do not yet differ substantially in 2050, these effects, and therefore their effects on agriculture, diverge under different mitigation pathways later in the century. But regardless of the scenario used to project future consumption patterns, the net effect of increasing atmospheric CO₂ concentrations is a decrease in availability of protein, iron, and zinc.

In conclusion, our approach to include effects of CO₂ on nutrition provides a unique assessment of future effects of climate change in the context of global food security. Integration of both productivity and nutrient content in the context of increasing CO₂ and climatic change, when applied to an economic model of the global agricultural sector, addresses an important knowledge gap regarding projected changes in global food security. This study shows that increasing concentrations of atmospheric CO₂ will slow progress in achieving decreases in global nutrient deficiencies and that this effect on nutrients is an important factor to consider in future agricultural modelling of the impact of climate change. Although this approach is an advancement in projecting future nutritional effects of climate change, additional work is needed to address the stated limitations, better incorporate this effect into crop yield models, and to quantify the projected effects on health associated with region-specific changes in per capita nutrient access.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Research in context

Evidence before this study

Many previous studies have reported that increasing atmospheric concentrations of carbon dioxide (CO₂) and other greenhouse gases and associated climate change will affect agricultural yields, although the direction and magnitude of these effects differ between crops and regions. Projections from global agricultural market models typically show increasing global food production per capita over the next few decades. Projections of global agricultural production per capita continue to show an increase when accounting for the effects of climate change over this timeframe, but the increase is slowed. In a largely separate field of study, a series of studies have been done in which important food crops are grown under conditions with varying concentrations of CO₂ to quantify the effects of increased concentrations of CO₂ on nutrient content. These studies have consistently found increases in the concentration of carbon in edible crop tissues along with decreases in other nutritional elements, such as protein (often proxied by nitrogen), iron, and zinc.

Added value of this study

This analysis augments past studies of the effect of climate change on global and regional agricultural productivity by proposing a novel approach to quantify effects on nutrient availability. We combined two datasets that measured nutrient content effects in key crops under different levels of CO₂ with structural economic projections of global diets in 2050, which consider future changes in agricultural production, prices, income, and consumption. By synthesising the effect of changes in both nutrient content and productivity of key agricultural commodities due to increased CO₂ and climate change (eg, temperature and precipitation changes), economic changes (eg, technological changes and market responses), and CO₂ yield fertilisation, we provide a more comprehensive estimate of the effect of climate change on agriculture and global nutrient availability. We found that, regardless of the baseline scenario used to project future consumption patterns, the net effect of increasing atmospheric concentrations of CO₂ will slow progress in achieving decreases in global nutrient deficiencies; in fact, inclusion of nutrient effects negates any benefits of CO₂ fertilisation on the availability of protein, iron, and zinc.

Implications of all the available evidence

Many countries with high levels of nutrient deficiency are also projected to be disproportionately affected in the future. Modelling studies that exclude the effects of increasing CO₂ on nutrient availability are not capturing the full effects of climate change on future agricultural productivity, consumption, and dietary outcomes, and might therefore be depicting an overly optimistic estimate of future global food security and dietary health.

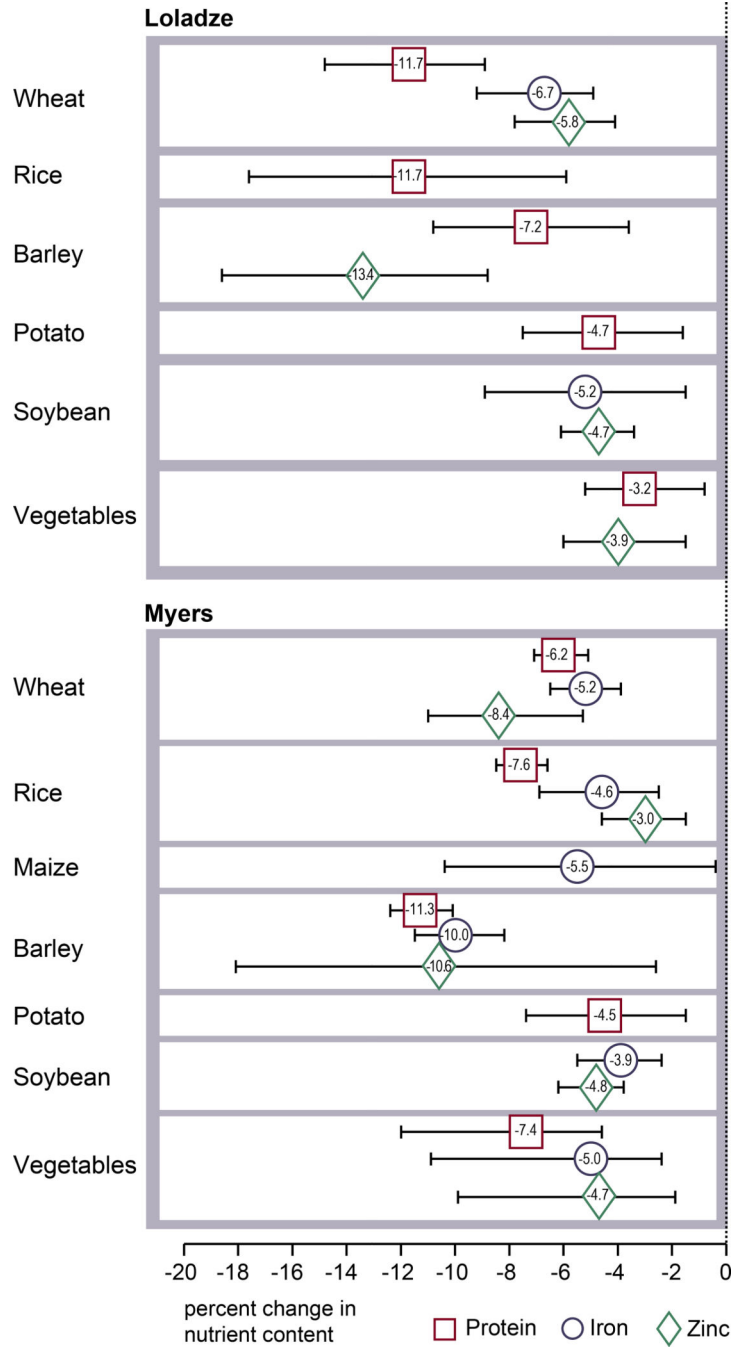
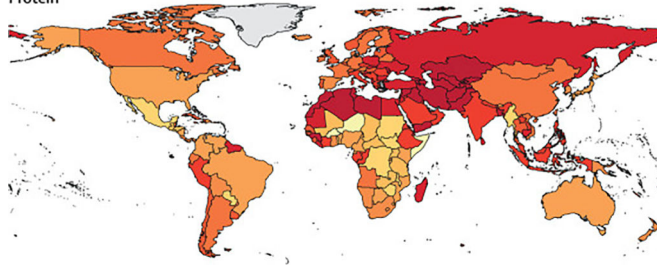


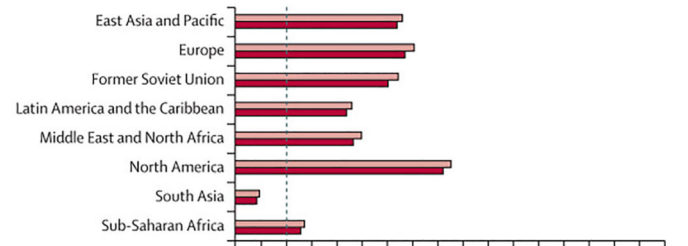
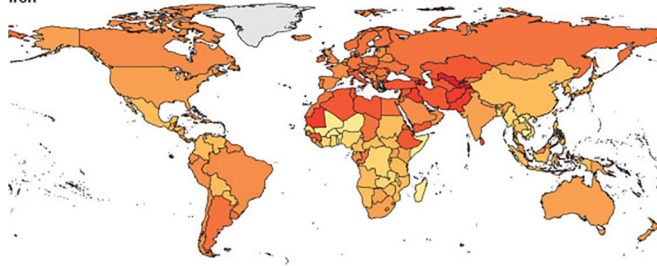
Figure 1: Carbon nutrient penalties
 Percentage change in protein, iron, and zinc from increased atmospheric CO₂ concentration (541 ppm) across seven groups of crop types available in Loladze¹⁸ and Myers et al¹⁹ datasets. Whiskers represent 95% CIs. Aggregate crop carbon nutrient penalties applied to commodities in the IMPACT model not shown in these datasets are in the appendix (pp 4–8). Where an observed carbon nutrient penalty is missing, data were either not available or did not meet inclusion criteria. IMPACT=International Model for Policy Analysis of Agricultural Commodities and Trade.

Loladze (2014)¹⁸

Protein



Iron



Zinc

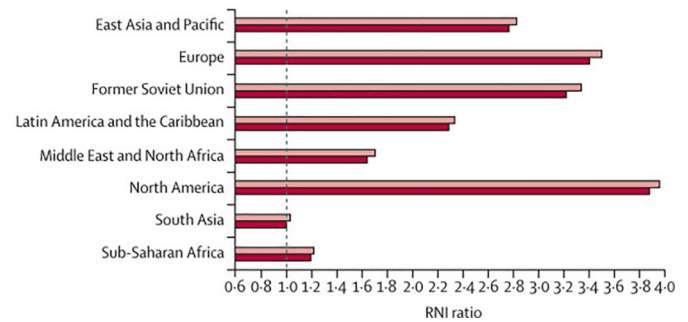
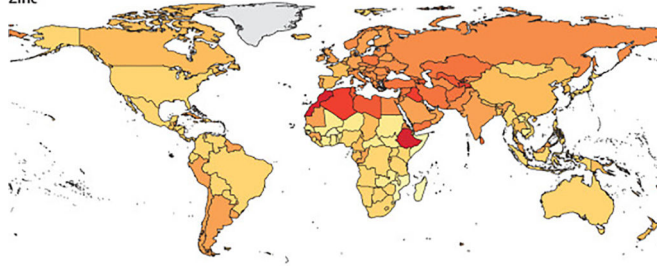
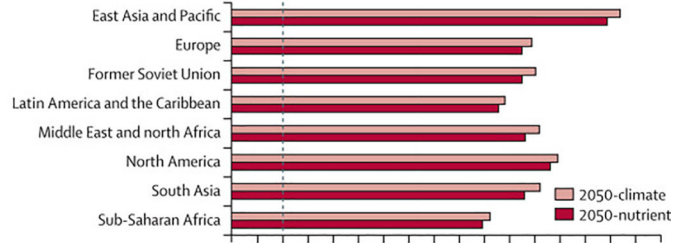
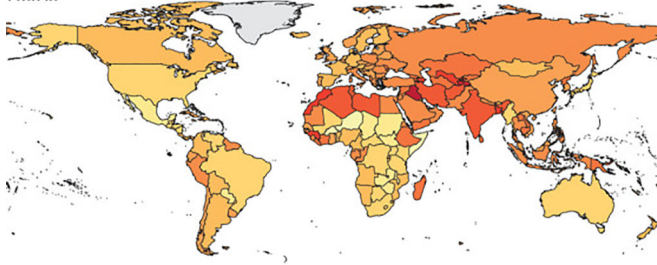


Figure 2: Net effects of increasing atmospheric CO₂ and climate change on nutrient availability in 2050 by use of the Loladze (2014)¹⁸ dataset

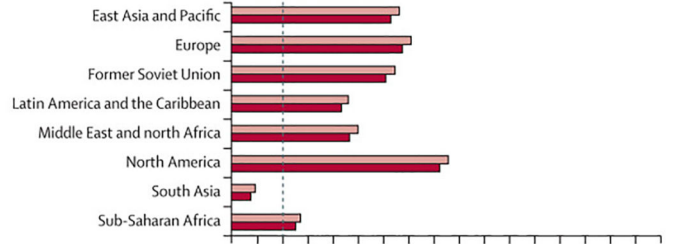
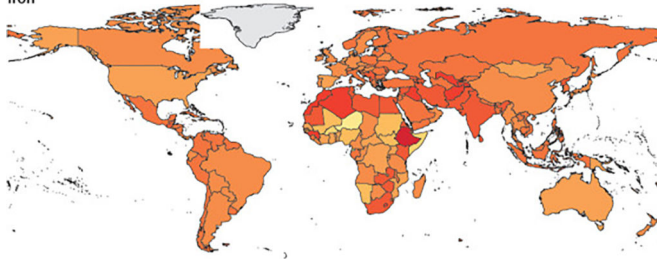
Maps show percentage change in 2050 per capita nutrient availability of protein, iron, and zinc for the 2050-nutrient scenario compared with the 2050-climate scenario. Graphs show change in RNI ratio in 2050 from the 2050-climate scenario to the 2050-nutrient scenario by region. The dotted vertical line indicates a 1:1 ratio of nutrients available to nutrients recommended (in mg or g per person per day). Results reflect the five global climate model average for the RCP8-5 scenario with CO₂ fertilisation with the Loladze (2014) dataset for carbon nutrient penalties. CO₂=carbon dioxide. RNI=recommended nutrient intake. RCP=Representative Concentration Pathway. ND=no data.

Myers et al (2014)¹⁹

Protein



Iron



Zinc

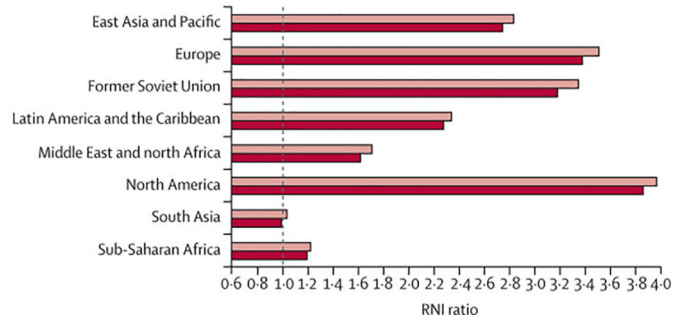
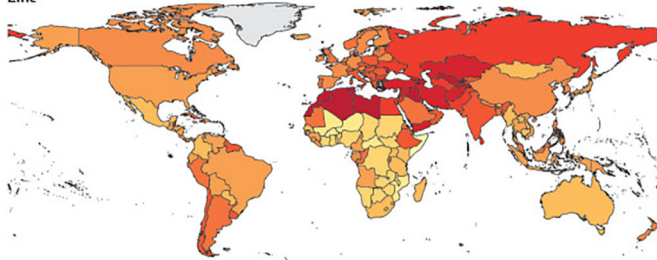


Figure 3: Net effects of increasing atmospheric CO₂ and climate change on nutrient availability in 2050 using Myers et al (2014)¹⁹ dataset

Maps show percentage change in 2050 per capita nutrient availability of protein, iron, and zinc for the 2050-nutrient scenario compared with the 2050-climate scenario. Graphs show the change in RNI ratio in 2050 from the 2050-climate scenario to the 2050-nutrient scenario by region. The dotted vertical line indicates a 1:1 ratio of nutrients available to nutrients recommended (in mg per person per day for iron and zinc and g per person per day for protein). Results reflect the five global climate model average for the RCP8.5 scenario with CO₂ fertilisation using the Myers et al (2014) dataset for carbon nutrient penalties. CO₂=carbon dioxide. RNI=recommended nutrient intake. RCP=Representative Concentration Pathway. ND=no data.

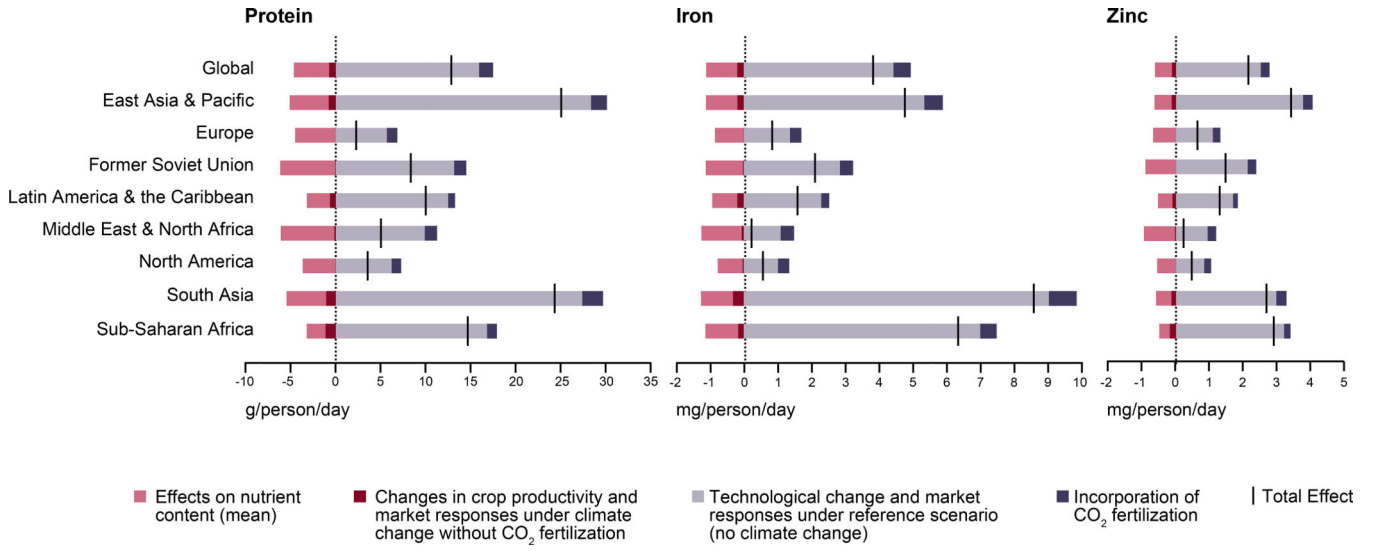


Figure 4: Total estimated effect on nutrient availability in 2050 compared with 2010
 The total effect, indicated by the vertical line across the bar, is the cumulative influence of all factors considered in this study. *Changes in nutrient concentrations are based on carbon nutrient penalties derived from the averaged Loladze (2014)¹⁸ and Myers et al (2014)¹⁹ datasets. CO₂=carbon dioxide.

Table:

Global and regional nutrient availability under RCP8.5

	2010-climate		2050-climate scenario		2050-nutrient scenarios	
			Loladze (2014) ¹⁸	Myers et al (2014) ¹⁹		
Protein availability, g per person per day						
Global	95-09	111-82	107-27 (105-68–108-84)	108-54 (107-56–109-34)		
East Asia and Pacific	104-81	134-15	129-23 (127-31–131-15)	130-40 (129-26–131-3)		
Europe	127-99	134-83	129-27 (127-68–130-77)	131-32 (130-37–132-16)		
Former Soviet Union	116-71	131-16	123-52 (121-33–125-56)	126-51 (125-39–127-58)		
Latin America and the Caribbean	98-18	110-76	107-73 (106-73–108-68)	108-69 (108-08–109-2)		
Middle East and north Africa	113-23	124-31	116-97 (114-80–119-00)	119-70 (118-64–120-69)		
North America	148-95	156-19	151-79 (150-49–153-01)	153-27 (152-40–154-00)		
Southern Asia	65-87	94-51	89-53 (87-66–91-4)	90-69 (89-52–91-62)		
Sub-Saharan Africa	66-40	83-15	80-82 (79-96–81-68)	81-32 (80-63–81-88)		
Iron availability, mg per person per day						
Global	23-78	28-50	27-70 (27-34–28-02)	27-47 (26-82–27-89)		
East Asia and Pacific	27-08	32-75	32-03 (31-7–32-32)	31-62 (30-85–32-10)		
Europe	22-73	24-42	23-55 (23-19–23-84)	23-58 (23-17–23-87)		
Former Soviet Union	24-06	27-25	26-11 (25-67–26-45)	26-20 (25-77–26-52)		
Latin America and the Caribbean	20-86	23-18	22-53 (22-2–22-83)	22-35 (21-79–22-76)		
Middle East and north Africa	27-64	29-06	27-89 (27-4–28-28)	27-86 (27-29–28-28)		
North America	24-52	25-82	25-10 (24-78–25-36)	25-07 (24-66–25-36)		
Southern Asia	17-31	26-79	26-02 (25-69–26-3)	25-67 (24-93–26-13)		
Sub-Saharan Africa	25-71	32-98	32-14 (31-66–32-62)	31-89 (31-12–32-39)		
Zinc availability, mg per person per day						
Global	14-52	17-17	16-75 (16-59–16-89)	16-59 (16-29–16-83)		
East Asia and Pacific	15-65	19-57	19-16 (19-19-31)	18-97 (18-63–19-23)		
Europe	19-59	20-91	20-33 (20-11–20-51)	20-12 (19-77–20-43)		
Former Soviet Union	19-17	21-55	20-79 (20-51–21-02)	20-49 (20-07–20-9)		
Latin America and the Caribbean	16-23	17-95	17-59 (17-47–17-7)	17-46 (17-22–17-65)		
Middle East and north Africa	19-52	20-68	19-90 (19-62–20-14)	19-61 (19-17–20-03)		

	2010-climate	2050-climate scenario	2050-nutrient scenarios	
			Loladze (2014) ¹⁸	Myers et al (2014) ¹⁹
North America	22-54	23-58	23-10 (22-93–23-25)	22-94 (22-64–23-19)
Southern Asia	9-73	12-87	12-49 (12-36–12-62)	12-32 (12-06–12-54)
Sub-Saharan Africa	11-58	14-78	14-50 (14-39–14-59)	14-46 (14-22–14-6)

Data are availability of nutrients in g or mg per person per day, with 95% CIs in parentheses. Data are for 2010 and in 2050 with and without CO₂ (541 ppm) effects on nutrient content. 2050-nutrient values include CO₂ fertilisation. RCP=Representative Concentration Pathway. CO₂=carbon dioxide