REVIEW

The Potential Impact of Climate Change on the Micronutrient-Rich Food Supply

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ABSTRACT

Micronutrient deficiencies are a major cause of morbidity and mortality in low- and middle-income countries worldwide. Climate change, characterized by increasing global surface temperatures and alterations in rainfall, has the capacity to affect the quality and accessibility of micronutrient-rich foods. The goals of this review are to summarize the potential effects of climate change and its consequences on agricultural yield and micronutrient quality, primarily zinc, iron, and vitamin A, of plant foods and upon the availability of animal foods, to discuss the implications for micronutrient deficiencies in the future, and to present possible mitigation and adaptive strategies. In general, the combination of increasing atmospheric carbon dioxide and rising temperature is predicted to reduce the overall yield of major staple crops, fruits, vegetables, and nuts, more than altering their micronutrient content. Crop yield is also reduced by elevated ground-level ozone and increased extreme weather events. Pollinator loss is expected to reduce the yield of many pollinator-dependent crops such as fruits, vegetables, and nuts. Sea-level rise resulting from melting of ice sheets and glaciers is predicted to result in coastal inundation, salt intrusion, and loss of coral reefs and mangrove forests, with an adverse impact upon coastal rice production and coastal fisheries. Global ocean fisheries catch is predicted to decline because of ocean warming and declining oxygen. Freshwater warming is also expected to alter ecosystems and reduce inland fisheries catch. In addition to limiting greenhouse gas production, adaptive strategies include postharvest fortification of foods; micronutrient supplementation; biofortification of staple crops with zinc and iron; plant breeding or genetic approaches to increase zinc, iron, and provitamin A carotenoid content of plant foods; and developing staple crops that are tolerant of abiotic stressors such as elevated carbon dioxide, elevated temperature, and increased soil salinity. *Adv Nutr* 2022;13:80–100.

Statement of Significance: This comprehensive review shows that climate change and its consequences are likely to affect micronutrient malnutrition by limiting the availability of micronutrient-rich plant and animal foods rather than their micronutrient content. Various mitigating and adaptive strategies should be considered to reduce the risk of micronutrient malnutrition in vulnerable populations in the face of climate change.

Keywords: climate change, food, iron deficiency, micronutrients, vitamin A deficiency, zinc deficiency

Introduction

Micronutrient deficiencies are a leading cause of morbidity and mortality worldwide, especially among young children and pregnant women. Vitamin A, zinc, and iron deficiencies are highly prevalent in low- and middle-income countries (LMICs) and affect an estimated 2 billion people worldwide (1). The world population is expected to grow from 7.7 billion people in 2019 to 9.7 billion by 2050 and 10.9 billion by 2100, according to the United Nations (2). Five different shared socioeconomic pathways (SSPs), based upon integrated scenarios for future societal development, project a global population that ranges from 8.5 to 9.9 billion in 2050, depending upon scenario (3). The population projections diverge further after 2050, with the "middle of the road" scenario, or SPP2, predicting a world population of ∼9.0 billion by 2100 (3). Providing sufficient food and preventing micronutrient deficiencies for this growing population will be major challenges in the face of climate change. The ideal goal is to meet these needs by providing food in a sustainable manner within the boundaries of the planet (4). Food systems face the dual challenge of increasing demand, growing environmental pressures, and the prospect that

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climate change is influencing the quality and quantity of food that is produced (5).

Plant foods provide a large proportion of micronutrient intake in LMICs (6, 7). In predominantly plant-based diets, dark-green leafy vegetables and orange and yellow fruits are rich sources of pro-vitamin A carotenoids, and legumes, nuts, and cereals are important sources of zinc and iron (7). Small-scale inland capture and coastal fisheries are also major sources of micronutrients for many populations in LMICs (8–10). Animal-source foods, such as eggs, beef, pork, chicken, and dairy products, are rich sources of vitamin A, zinc, and iron, but are relatively expensive and not regularly consumed by poorer families. Any factors that limit the availability of staple crops such as cereals can lead to global increases in food prices and greater vulnerability of poor populations to micronutrient malnutrition (11, 12).

Climate change encompasses a broad set of environmental processes related to rising atmospheric carbon dioxide (CO_2) and increasing global surface temperatures (13). These processes include more frequent occurrence of extreme weather events, degradation of the cryosphere, sea-level rise, increase in ocean hypoxia, land degradation, elevated ground-level ozone, and greater abiotic and biotic stress to plants. Both the yield and the micronutrient concentrations of foods can be affected by climate change and increase the risk of micronutrient deficiencies in the general population and especially in vulnerable populations. The goals of this scoping review are to summarize the potential effects of climate change on the yield and micronutrient quality of plant and animal foods and their implications for micronutrient deficiencies in the future and to discuss possible mitigation and adaptation strategies. A conceptual model for this review is shown in **Figure 1**. Climate change consists of abiotic and biotic factors that influence the quality and yield of plants and animals that provide micronutrients in the diet.

Rising Atmospheric CO_2 Concentrations and Increasing Temperature

The major greenhouse gas (GHG) arising from human activities is carbon dioxide (14). Prior to the Industrial Revolution, atmospheric carbon dioxide concentrations were relatively stable at ∼280 ppm for at least 10,000 y (13). Atmospheric carbon dioxide has increased steadily by 2–3 ppm annually (15) and is predicted to increase from 415 ppm in 2020 (16) to 550 ppm by 2050 (14). Without mitigating activities, atmospheric carbon dioxide is expected to double between now and the end of the century (14).

The accumulation of GHGs in the atmosphere alters the balance between incoming solar radiation, which heats the Earth's surface, and re-emitted infrared energy, which is absorbed by atmospheric carbon dioxide and water vapor, with the net effect of driving surface heating, or global warming (17). Human activities have resulted in ∼1.0°C of global warming above preindustrial levels, with warming currently increasing at 0.2°C per decade (18). Warming above the global average is occurring more over land than water and in the Arctic region (18). Global warming is likely to reach 1.5°C above preindustrial levels between 2030 and 2050 if it continues to increase at the current rate (18).

The United Nations Intergovernmental Panel on Climate Change (IPCC) has adopted representative concentration pathways (RCPs)—scenarios that include emissions and concentrations of GHGs, aerosols, and chemically active gases as well as changes in land use over time—for climate modeling. There were 4 original RCPs, with RCP2.6 representing low GHG emissions and high mitigation that gives a 2 out of 3 chance to limit global warming below 2°C by 2100, and RCP8.5 representing a high GHG scenario with the absence of policies to combat climate change, leading to continued and sustained growth in GHG concentrations (19). RCP4.5 and RCP6.0 represented intermediate scenarios. The RCPs have been used to model the effects of climate change on crop yields and nutrient quality and to estimate future trajectories and effects on climate change, as noted further below.

Effects of rising carbon dioxide and temperature on major crops

As carbon dioxide concentrations rise, most plants respond by growing faster (20). The impacts of elevated atmospheric carbon dioxide, as an isolated factor, on plants were originally studied using open top chambers (OTCs). Free-air carbon dioxide enrichment (FACE), a technique in which plants are grown under elevatedcarbon dioxide in natural and fully open-air conditions, gradually replaced OTCs for most crop studies (21). Plants can be distinguished into 2 groups, C_3 and C_4, based on the type of photosynthesis. The first stable products of photosynthesis are either three-carbon molecules in C_3 plants or four-carbon molecules in C_4 plants. C_3 plants constitute 95% of species on the planet (22) and include most food crops such as wheat, rice, barley, potato, legumes, nuts, fruit, and vegetables (23). The few food crops that are C_4 species include maize, sugarcane, sorghum, and millet. In general, C_3 food crops have modest increases in yield when grown under elevated atmospheric carbon dioxide using FACE. In contrast, elevated atmospheric carbon dioxide, as an isolated factor, has no direct effect upon carbon uptake by C_4 plants (24), but some studies suggest that yield of C_4 crop plants may increase under drought conditions (25, 26).

Elevated carbon dioxide, as an isolated factor, has been shown to increase the agricultural yield for crops such as wheat, rice, potato, and legumes (21, 27–29). Plants increase

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Supplemental Tables 1–4 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/advances/.
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Abbreviations used: CESM, Community Earth System Model; EEZ, exclusive economic zone; FACE, free-air carbon dioxide enrichment; GHG, greenhouse gas; GMSL, global mean sea level; IFAP, industrial food animal production; LECZ, low elevation coastal zone; LMIC, low- and middle-income country; OTC, open-top chamber; RCP, representative concentration pathway; SSP, shared socioeconomic pathway; T-FACE, temperature free-air carbon dioxide enrichment.

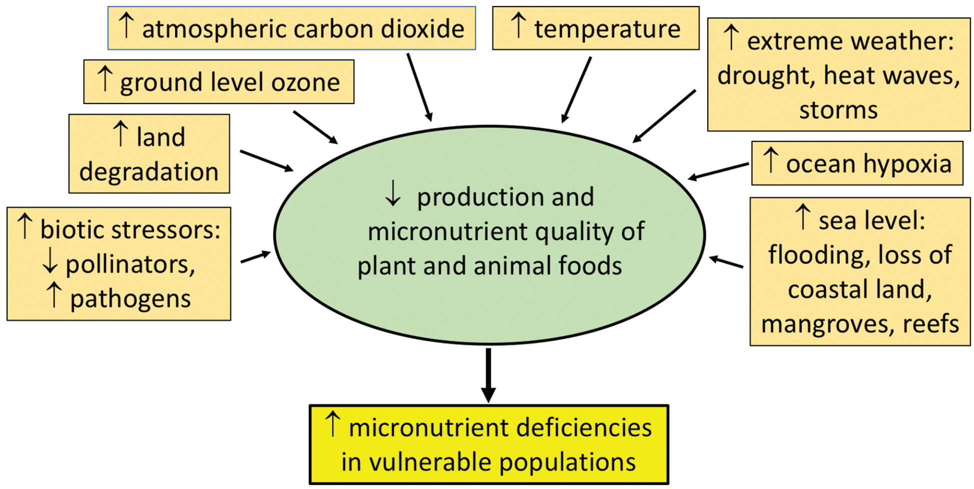

FIGURE 1 Conceptual model of climate change and micronutrient deficiencies.

the synthesis of carbohydrates when exposed to higher levels of atmospheric carbon dioxide. The increase in carbohydrate content with elevated carbon dioxide appears to dilute the overall mineral content of plant tissues by 8% (28). Elevated carbon dioxide increased the carbon content of plants but reduced the nitrogen, potassium, phosphorus, calcium, sulfur, magnesium, iron, zinc, and copper content (28). The reduction in mineral content has been observed regardless of whether determined by FACE or non-FACE studies, by geographic location, and in plant groups or tissues (28). Elevated atmospheric carbon dioxide also reduces canopy transpiration and decreases nutrient uptake by the roots (30).

In contrast to elevated carbon dioxide, elevated temperature is expected to have a detrimental effect upon cereal, vegetable, and legume production. For each 1°C increase in temperature, the yield of wheat and barley is reduced by 5–6% (31). Rice is sensitive to changes in temperature (32), and grain yield of rice is reduced by global warming (33). In Africa, rice yields are projected to drop by 24% in 2070 compared with 2000 under RCP8.5 (34), and global warming of 2.0°C would reduce maize yield (35). In general, most vegetable crops require low temperature for their cultivation, and even slight increases in temperature will reduce crop productivity (36). Legumes are sensitive to heat stress (37) and increasing temperatures will reduce crop yields (38).

In order to study the effect of both elevated carbon dioxide and elevated temperature on cereals and other crops, which is more consistent with future climate change projections, a more recent platform has been developed known as temperature FACE (T-FACE). This experimental setup involves FACE combined with temperature-controlled infrared heaters to simulate conditions of both elevated carbon dioxide and elevated temperature that are anticipated by the middle and end of the 21st century. OTC, FACE, and T-FACE platforms are illustrated in **Figure 2**. The experimental evidence for the effects of elevated carbon dioxide and elevated temperature, as isolated factors, elevated carbon dioxide and elevated temperature combined, and other stressors on major crops is discussed in greater detail in the following sections on rice, wheat, legumes, vegetables and fruit, and nuts. .

Rice.

Rice is the staple food of ∼3.5 billion people worldwide (39). Milled rice production worldwide in 2019 was 755 million tons (40). The 10 countries with the largest consumption of rice as a fraction of total available calories are Bangladesh, Cambodia, China, Indonesia, Lao People's Democratic Republic, Madagascar, Myanmar, Philippines, Thailand, and Vietnam (41). Rice provides up to 50% of the dietary caloric supply and a substantial part of protein intake for >500 million people living in poverty in Asia (39). Rice consumption is steadily growing in sub-Saharan Africa, the Caribbean, and Latin America (39). The leading producers of rice worldwide are China and India, followed by Indonesia, Bangladesh, Vietnam, Myanmar, Thailand, and the Philippines (40).

The impact of elevated carbon dioxide on overall grain yield and upon zinc and iron concentrations in rice grains has been studied in OTC, FACE, and T-FACE studies conducted in Asia, Europe, and Australia (42–58). There is considerable heterogeneity in the type of study, number of replicates, number of growing seasons, cultivars utilized, and geographic location of the testing sites (**Supplemental Table 1**). Most studies showed that elevated temperature reduced the yield of rice, with a range of 7–21% reductions observed compared with ambient temperature (43, 47, 49, 50). The combination of elevated carbon dioxide and temperature generally reduced the yield of rice (47–52) (**Table 1**). A meta-analysis suggested that the combination of elevated carbon dioxide and temperature may increase the yield of rice by 10.1% (59); however, the analysis was limited to only 5 studies and did not include 1 OTC study (48) and 2 more recent T-FACE studies (43, 44).

Elevated carbon dioxide concentrations have been shown to decrease (45, 46, 48, 54, 58), increase (53),

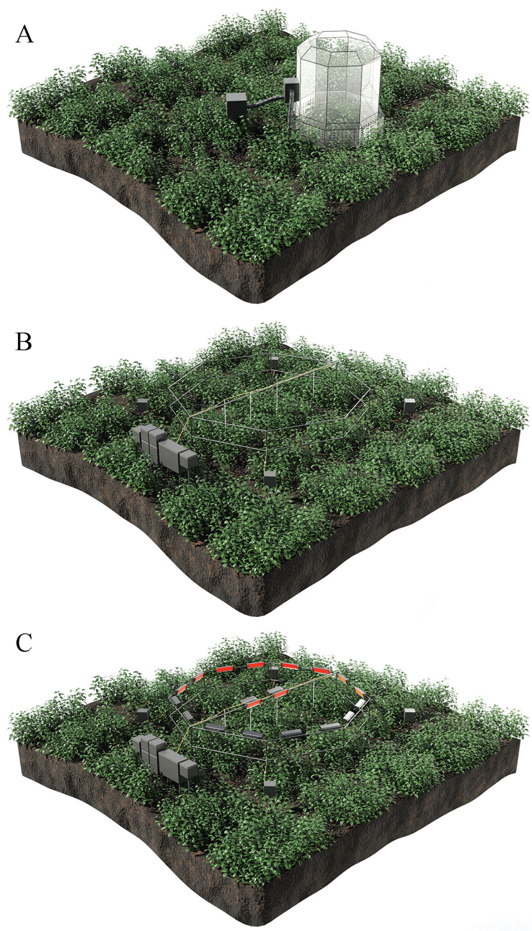

FIGURE 2 Platforms for assessing plant growth and yield in controlled environments: (A) open-top chamber (OTC), (B) free-air carbon dioxide enrichment (FACE), (C) temperature free-air carbon dioxide enrichment (T-FACE).

or have no effect (57) on zinc concentrations, and to decrease (46, 48), increase (53), or have no effect (45, 56, 58) on iron concentrations in rice grains (Table 1). Elevated carbon dioxide concentrations have been shown to increase the yield of rice grains (43, 47–51, 55–58). Two independent meta-analyses show that elevated carbon dioxide reduces zinc concentrations by 3% and iron concentrations by 5% in rice grains compared with ambient carbon dioxide levels (60, 61). It is not possible to conclude on the basis of these meta-analyses that climate change will have an adverse impact upon zinc and iron concentrations in rice in the future, since these meta-analyses only addressed the effect of elevated carbon dioxide alone. T-FACE experiments show that the combination of elevated carbon dioxide and temperature will increase rice grain concentrations of both iron and zinc when compared with current conditions (42, 43). Although elevated carbon dioxide reduces zinc and iron concentrations in rice grains, elevated temperatures increase zinc and iron concentrations, offsetting the reductions due to elevated carbon dioxide (43). The combination of elevated carbon dioxide and temperature increased the concentrations of cadmium and lead in rice grains, raising potential issues about metal toxicity in rice in the future with climate change (43).

Wheat.

Wheat (*Triticum aestivum*) is the second most important energy source for humans and has an annual global production of ~762 million tons (40). In some micronutrient-deficient populations, wheat is the dominant staple in the diet, providing >50% of daily energy intake (62). The impacts of elevated carbon dioxide and elevated temperature on wheat yield and on zinc and iron concentrations in wheat grains have been studied in Europe, Turkey, China, and Australia (43, 63–70) (**Table 2**), with considerable heterogeneity between studies (**Supplemental Table 2**). Elevated carbon dioxide concentrations, as an isolated factor, have been shown to increase (43, 64, 65, 71, 72) or to have no effect (50, 63, 69) on the yield of wheat. Elevated carbon dioxide concentrations have been shown to decrease (66–68, 71, 73, 72, 74) or have no effect (69, 75, 76) on zinc concentrations, and to decrease (67, 69, 71, 73, 75, 74) or have no effect (66, 77, 76) on iron concentrations in wheat grains (Table 2). An early review concluded that elevated carbon dioxide reduced wheat grain zinc and iron by 13% and 18%, respectively (78). Two independent meta-analyses showed that elevated carbon dioxide, as an isolated factor, reduces zinc concentrations by 9% and iron concentrations by 5–7% in wheat grains (60, 79).

When the combined effects of both elevated carbon dioxide and temperature were studied together, elevated temperature offset the reductions of zinc and iron concentrations in wheat grains (43, 77). The combination of elevated carbon dioxide and temperature increased the concentrations of cadmium and lead in wheat grains, raising similar issues about metal toxicity as with rice with regard to climate change (43). Elevated carbon dioxide and temperature reduced the yield of wheat (43, 52, 65, 70), suggesting that the main effect of climate change on zinc and iron deficiencies will be to limit the yield of wheat rather than alter the zinc and iron content of wheat grains alone.

Legumes.

Legumes, an important source of iron, zinc, B-complex vitamins, and protein, are generally consumed worldwide, with the highest consumption in Latin America and the Caribbean, sub-Saharan Africa, and South Asia (80). Soybean accounts for nearly three-quarters of global legume production; however, most soybean is used as animal feed and cooking oil, and only ~6% is used directly as food for humans (80). Other legumes of importance in the human diet include peanut, common bean, field pea, chickpea, cowpea, fava bean, lentil, pigeon pea, lupin, and Bambara bean (80). Both chickpea and lentil are cool-season legumes that are more sensitive to the effects of global warming (81, 82).

The impacts of elevated carbon dioxide, elevated temperature, and other conditions upon zinc and iron concentrations and total yield of legumes have been examined in studies conducted in the United States, Brazil, Asia, and Australia

TABLE 1 Effect of elevated carbon dioxide, elevated temperature, and other conditions on the zinc and on content and yield of rice[1]

Location	Study	Growing conditions	Micronutrients	Yield	Reference
China	T-FACE	CO_2: 384 vs. 574 ppm Temperature: ambient vs. +1.4°C	Zn ↑ ~42% (eCO_2 + eT) Fe ↑ ~23% (eCO_2 + eT)	Not reported	42
China	T-FACE	CO_2: ambient vs. 510 ppm Temperature: ambient vs. +1.8°C	Zn ↓ 8% (eCO_2) Zn ↑ 7% (eT) Fe ↓ 20% (eCO_2) Fe ↑ 30% (eT)	↑ 11% (eCO_2) ↓ 12% (eT)	43
China	T-FACE	CO_2: 390 vs 590 ppm Temperature: ambient vs. +1.5°C	Not reported	↓ 5% (eCO_2 + eT) in 2015 ↓ 12% (eCO_2 + eT) in 2016	44
Japan	FACE	CO_2: 370 vs 700 ppm; 9 cultivars	Zn ↓ 6% (eCO_2) Fe ↔ (eCO_2)	Not reported	45
Japan and China	FACE	CO_2: 395 vs. 568-590 ppm; 18 cultivars	Zn ↓ 5% (eCO_2) overall Zn ↓ 10–15% (eCO_2), with some cultivars Fe ↓ 8% (eCO_2), overall Fe ↓ 10–20% (eCO_2), with some cultivars	Not reported	46
China	T-FACE	CO_2: ambient vs. 590 ppm; Temperature: ambient vs. +1.0°C	Not reported	↑ 15% (eCO_2), in 2015 ↑ 13% (eCO_2), in 2016 ↓ 8% (eT), in 2015 ↓ 21% (eT), in 2016 ↓ 4% (eCO_2 + eT) in 2015 ↓ 14% (eCO_2 + eT) in 2016	47
India	OTC	CO_2: 396 vs. 596 ppm; Heat stress: ambient vs. +3–4°C; 2 cultivars	Zn ↓ 11–16% (eCO_2) Zn ↓ 10–23% (eCO_2 + eT) Fe ↓ 12–20% (eCO_2) Fe ↓ 14–23% (eCO_2 + eT)	↑ 14–20% (eCO_2) ↓ 9–15% (eCO_2 + eT)	48
China	T-FACE	CO_2: ambient vs. 590 ppm; Temperature: ambient vs. +1.0°C	Not reported	↑ 6% (eCO_2), in 2013 ↑ 10% (eCO_2), in 2014 ↓ 25% (eT), in 2013 ↓ 11% (eT), in 2014 ↓ 12% (eCO_2 + eT) in 2013 ↓ 7% (eCO_2 + eT) in 2014	49
China	T-FACE	CO_2: ambient vs. 500 ppm; Temperature: ambient vs. +2.0°C	Not reported	↑ 8% (eCO_2) ↓ 10% (eT) ↓ 5% (eCO_2 + eT)	50
Japan	FACE	CO_2: 382 vs. 574 ppm Water and soil temperature: ambient vs. +2.0°C	Not reported	↑ 14% (eCO_2) ↔ (eT)	51
China	T-FACE	CO_2: ambient vs. 500 ppm; Temperature: ambient vs. +1.5°C, +2.0°C	Not reported	↓ 17–35% (eCO_2 + eT)	52
Portugal	OTC	CO_2: 375 vs. 550 ppm	Zn ↑ 8% (eCO_2) Fe ↑ 14% (eCO_2)	Not reported	53
China	Glass house	CO_2: ambient vs. 600 ppm; plus eO_3	Zn ↔ (eCO_2 + ambient O_3) Zn ↔ (eCO_2 + eO_3)	Not reported	54
Japan	FACE	CO_2: ambient vs. 577 ppm; 8 cultivars	Not reported	↑ 17% (eCO_2)	55

(*Continued*)

TABLE 1 *(Continued)*

Location	Study	Growing conditions	Micronutrients	Yield	Reference
China	FACE	CO_2: ambient vs. 572 ppm; range of nitrogen fertilizer	Fe ↔ (eCO_2)	↑ 11% (eCO_2)	56
Japan	FACE	CO_2: ambient vs. 625 ppm or 570 ppm	Zn ↔ (eCO_2, 625 ppm) Fe ↔ (eCO_2, 625 ppm) Zn ↔ (eCO_2, 570 ppm) Fe ↔ (eCO_2, 570 ppm)	↑ 14% (eCO_2)	57
Australia	OTC	CO_2: 350 vs. 700 ppm plus range of P supply	Zn ↓ 14% (eCO_2 + 0 P) Zn ↓ 16% (eCO_2 + 240 mg/kg P) Fe ↔ (eCO_2 + 0 P) Fe ↓ 18% (eCO_2 + 240 mg/kg P)	↑ 58% (eCO_2)	58

[1]eCO_2, elevated carbon dioxide; eO_3, elevated ozone; eT, elevated temperature; FACE, free-air carbon dioxide enrichment; OTC, open-top container; T-FACE, temperature free-air carbon dioxide enrichment, arrow up denotes increase, arrow down denotes decrease, arrow side-to-side denotes no change.

(64, 83–94) (**Table 3**). These studies have been limited to a small number of legume species (**Supplemental Table 3**). Elevated carbon dioxide concentrations, as an isolated factor, increase the yield of soybean (92), chickpea (64), lentil (88), and common bean (93, 94). Elevated temperature alone decreases the yield of peanuts (95). In chickpeas, elevated carbon dioxide alone reduced zinc concentration but had no impact upon iron concentration (90). Elevated carbon dioxide alone reduced zinc and iron concentrations in both lentils and fava beans (85). Zinc concentrations were reduced by elevated carbon dioxide alone in some soybean cultivars (86). A meta-analysis showed that elevated carbon dioxide reduced zinc and iron concentrations in both soybeans and field peas (61). Elevated carbon dioxide and elevated temperatures combined had no impact upon zinc and iron concentrations in soybean (83). The overall yield of legumes is threatened by climate change, as elevated carbon dioxide and elevated temperatures combined have been shown to reduce the yield of soybean (84), lentil (88), peanut (91), and common bean (94). Currently, the common bean is cultivated by smallholder farmers in Zambia, Zimbabwe, Tanzania, western Malawi, and northern Mozambique. A study using the EcoCrop model developed by United Nations FAO predicts that most of this region will no longer be suitable for cultivation of the common bean by 2050 given climate change and predicted drought conditions (96).

Vegetables and fruit.

Dark-green leafy vegetables and orange and yellow fruits are important plant sources of provitamin A carotenoids. Vegetables provide a substantial amount of iron and zinc among populations with a high intake of plant-based foods. The impact of elevated carbon dioxide upon overall yield and zinc, iron, and carotenoid concentrations in vegetables and fruit has been studied in Asia, Europe, the United States, and Australia, mostly using OTCs, growth chambers, or greenhouses (45, 97–113) (**Table 4**). The effect of climate change has been studied only in a limited number of vegetables and fruit species and cultivars (**Supplemental Table 4**). Meta-analyses and systematic reviews show that elevated carbon dioxide alone increases the yield of vegetables by 34% (114) and fruit by 38% (95); however, elevated temperature attenuates the stimulation and yield by elevated carbon dioxide (95). Elevated carbon dioxide, as an isolated factor, generally reduces the iron and zinc content of vegetables, although there can be differences by cultivar and soil conditions (Table 4). The impact of elevated carbon dioxide alone upon the carotenoid content of crops has not been consistent. Elevated carbon dioxide had no effect upon carotenoid concentrations in sweet pepper (100), spinach (105), and sweet potato (113), but reduced carotenoid concentrations in lettuce (108) and canola (111). A meta-analysis suggests that elevated carbon dioxide, as an isolated factor, reduces the carotenoid concentration of plants by 15% (115). This meta-analysis was based upon a diversity of plants, including non-crop plants, and it is unclear if these

TABLE 2 Effect of elevated carbon dioxide, elevated temperature, and other conditions on the zinc and iron content and yield of wheat[1]

Location	Study	Growing conditions	Micronutrients	Yield	Reference
China	T-FACE	CO_2: ambient vs. 510 ppm Temperature: ambient vs. +1.8°C	Zn ↓ 14% (eCO_2) Zn ↑ 4% (eT) Fe ↓ 3% (eCO_2) Fe ↑ 18% (eT)	↑ 11% (eCO_2) ↓ 12% (eT)	43
Germany, Italy, China, Australia, USA	FACE	CO_2: 400 vs. 550 ppm	Not reported	↔ (eCO_2) Germany ↔ (eCO_2) Italy ↔ (eCO_2) China ↔ (eCO_2) Australia ↑ ~25% (eCO_2) USA	63
India	FACE	CO_2: 390 vs. 550 ppm	not reported	↑ 16% (eCO_2)	64
Turkey	OTC	CO_2: 400 vs. 700 ppm Temperature: ambient vs. +3°C Soil: adequate vs. low N Soil: adequate vs. low Zn	Zn ↑ 15% (eCO_2 + eT) overall	↓ 12% (eCO_2 + eT) overall	65
Australia	FACE	CO_2: 390 vs. 550 ppm	Zn ↓ 10% (eCO_2) Fe ↔ (eCO_2)	Not reported	66
Italy	FACE	CO_2: 400 vs. 570 ppm	Zn ↓ 22% (eCO_2) Fe ↓ 27% (eCO_2)	Not reported	67
Turkey	OTC	CO_2: 400 vs. 700 ppm Water: watered vs. drought Soil: adequate vs. low Zn	Zn ↓ 10% (eCO_2) watered Zn ↓ 23% (eCO_2) drought Zn ↓ 22% (eCO_2) adequate soil Zn Zn ↓ 26% (eCO_2) low soil Zn	↑ 21% (eCO_2) watered ↑ 47% (eCO_2) drought ↑ 27% (eCO_2) adequate soil Zn ↑ 38% (eCO_2) low soil Zn	68
China	T-FACE	CO_2: ambient vs. 500 ppm Temperature: ambient vs. +2.0°C	Not reported	↔ (eCO_2) ↓ 26% (eT) ↔ (eCO_2 + eT)	50
China	T-FACE	CO_2: ambient vs. 500 ppm Temperature: ambient vs. +1.5°C, +2.0°C	Not reported	↓ 10–12% (eCO_2 + eT)	52
Germany	FACE	CO_2: ambient vs. 571 ppm	Zn ↔ (eCO_2) Fe ↓ 6% (eCO_2)	↔ (eCO_2)	69
Australia	Tunnel house	CO_2: ambient vs. 700 ppm Temperature: ambient vs. +2°C, +4°C, or +6°C Water: watered vs. drought Two cultivars: Janz and 38–19	Not reported	↓ (eCO_2 + eT) both cultivars both watered and drought conditions	70
Australia	FACE	CO_2: 384 vs. 550 ppm	Zn ↓ 22% (eCO_2) Fe ↓ 10% (eCO_2)	↑ 48–61% (eCO_2)	71
Germany	FACE	CO_2: 375 vs. 550 ppm	Zn ↓ 9% (eCO_2) Fe ↓ 15% (eCO_2)	Not reported	72
China	OTC	CO_2: 350 vs. 700 ppm Water: watered vs. drought	Zn ↓ 33% (eCO_2)	↑ 166% (eCO_2) watered ↑ 78% (eCO_2) drought	73
Spain	Temperature gradient funnel	CO_2: 350 vs. 700 ppm, Temperature: ambient vs. +4°C	Fe ↔ (eCO_2)	Not reported	74

(*Continued*)

TABLE 2 (*Continued*)

Location	Study	Growing conditions	Micronutrients	Yield	Reference
UK, Germany, Belgium, Denmark, Ireland, the Netherlands	OTC	CO_2: 360 vs. 680 ppm	Zn ↔ (eCO_2) Fe ↓ 18% (eCO_2)	Not reported	75
Germany	OTC	CO_2: 361, 523, or 639 ppm Soil N: 50 vs. 270 kg/h	Zn ↓ 13% (eCO_2) at 523 ppm, N 150 kg/h Zn ↓ 23% (eCO_2) at 523 ppm, N 270 kg/h Zn ↓ 13% (eCO_2) at 639 ppm, N 150 kg/h Zn ↓ 18% (eCO_2) at 639 ppm, N 270 kg/h Fe ↓ 18% (eCO_2) at 523 ppm, N 150 kg/h Fe ↓ 28% (eCO_2) at 523 ppm, N 270 kg/h Fe ↓ 25% (eCO_2) at 639 ppm, N 150 kg/h Fe ↓ 35% (eCO_2) at 639 ppm, N 270 kg/h	Not reported	76
Germany	OTC	CO_2: 384, 551, 718 ppm	Zn ↔ (eCO_2) Fe ↔ (eCO_2)	Not reported	77

[1] eCO_2, elevated carbon dioxide; eT, elevated temperature; FACE, free-air carbon dioxide enrichment; OTC, open-top container; T-FACE, temperature free-air carbon dioxide enrichment, arrow up denotes increase, arrow down denotes decrease, arrow side-to-side denotes no change.

results can be generalized to vegetables and fruits that are important sources of provitamin A carotenoids.

Mango, an important source of vitamin A in many LMICs, is sensitive to rainfall and temperature (116). Climate change is already affecting the cultivation and production of mango, with shifts to higher elevations and higher latitudes that are more amenable to flowering and fruit development (116, 117). Potato yields are expected to decline across India with climate change (118).

Nuts.

The potential impact of elevated carbon dioxide and elevated temperature upon micronutrient quality and yield of nuts has not been well characterized (95). Temperate nut species require exposure to chilling conditions in the winter in order to break dormancy and to produce higher yields (119). Climate change is affecting winter chill and is expected to adversely affect nut production in some regions. Analysis of historic chill records and modeling of future chill estimates show that the production of almonds and pistachios in central Tunisia may no longer be viable in the future because of insufficient chilling (120). These findings suggest that temperate nut production in other parts of the Mediterranean region may be similarly affected. Other areas of temperate nut production that may be affected by chill losses include southern Brazil and South Africa (119). Tropical nut production is also likely to be affected by climate change. Cashew is sensitive to rainfall and temperature, particularly during flowering, and is considered highly susceptible to climate change (121). Elevated carbon dioxide and temperature are expected to adversely impact coconut production in areas of India (122).

Effects of ground-level ozone on major crops

In preindustrial times, the concentration of ground-level ozone was <20 ppb. Ground-level ozone is formed through photochemical reactions with products of anthropogenic emissions such as carbon monoxide, nitrogen oxides, methane, and non-methane volatile organic compounds. The rate of ground-level ozone formation increases with elevated atmospheric temperature (123). Current ground-level ozone concentrations in the northern mid-latitudes are ∼30 to 50 ppb (124). Since the 1950s, ground-level ozone levels have increased in the Northern Hemisphere by 1–5 ppb per decade and in the Southern Hemisphere by 1–2 ppb per decade (124). Geographic regions with higher ground-level ozone include northeastern India, eastern China, west and southern Africa, and the eastern United States (125). Ozone adversely affects plants by reducing photosynthesis and yield (124, 126).

A meta-analysis of wheat quality showed that elevated ground-level ozone, as an isolated factor, increases the zinc concentration of wheat grains but has no effect on the iron concentration (127). There has been a paucity of studies examining the impact of elevated carbon dioxide and elevated ozone combined upon micronutrient concentrations in crops. Elevated carbon dioxide and elevated ozone had no

TABLE 3 Effect of elevated carbon dioxide, elevated temperature, and other conditions on the zinc and iron content and yield of legumes[1]

Location	Study	Growing conditions	Micronutrients	Yield	Reference
India	FACE	CO_2: 390 vs. 550 ppm	Not reported	↑ 22% (eCO_2) chickpea	64
USA	T-FACE	CO_2: 400 vs. 600 ppm Temperature: ambient vs. +2.7°C day and +3.4°C night	Zn ↔ (eCO_2 + eT) soybean Fe ↔ (eCO_2 + eT) soybean	↔ (eCO_2 + eT) soybean	83
Brazil	OTC	CO_2: 380 vs. 800 ppm Temperature: ambient vs. +4°C	Not reported	↓ 11% (eCO_2 + eT) soybean	84
Australia	FACE	CO_2: 400 vs. 550 ppm Water: dry vs. wet	Zn ↓ 6% (eCO_2), wet, lentil Zn ↓ 24% (eCO_2), dry, lentil Fe ↓ 4% (eCO_2) wet, lentil Fe ↓ 20% (eCO_2) dry, lentil Zn ↓ 9% (eCO_2) wet, fava bean Zn ↓ 25% (eCO_2) dry, fava bean Fe ↓ 8% (eCO_2) wet, fava bean Fe ↓ 22% (eCO_2) dry, fava bean	Not reported	85
China	OTC	CO_2: 390 vs. 550 ppm, 4 soybean cultivars: ZK-1, ZK-2, ZK-3, HD	Zn ↓ 10% (eCO_2) ZK-1 Zn ↑ 14% (eCO_2) ZK-2 Zn ↓ 22% (eCO_2) ZK-3 Zn ↑ 14% (eCO_2) HD Fe ↓ 10% (eCO_2) ZK-1 Fe ↓ 8% (eCO_2) ZK-2 Fe ↓ 6% (eCO_2) ZK-3 Fe ↓ 13% (eCO_2) HD	Not reported	86
Australia	FACE	CO_2: ambient vs. 550 ppm Temperature: ambient vs. 38–40°C × 3 d to mimic heat wave	Not reported	↓ 33% (ambient CO_2 + eT) lentil ↓ 33% (eCO_2 + eT) lentil	87
Australia	FACE	CO_2: ambient vs. 550 ppm	Not reported	↑ 18–138% (eCO_2) lentil	88
USA	OTC	CO_2: 360 vs. 700 ppm Temperature: 26°C day, 16°C night vs. 45°C day, 35°C night	Zn ↓ 20% (eCO_2 + eT) soybean Fe ↓ 36% (eCO_2 + eT) soybean	Not reported	89
India	OTC	CO_2: ambient vs. 580 ppm	Zn ↓ 36–41% (eCO_2) chickpea Fe ↔ (eCO_2) chickpea	Not reported	90
USA	Growth chamber	CO_2: 380 vs. 550 ppm Temperature: ambient vs. +2.5°C, +5°C Peanut (Georgia Green, Pronto cultivars)	Not reported	↓ 82% (eCO_2 + eT + 2.5°C), Georgia Green ↓ 92% (eCO_2 + eT + 5°C), Georgia Green ↓ 46% (eCO_2 + eT + 2.5°C), Pronto ↓ 91% (eCO_2 + eT + 5°C), Pronto	91
India	OTC	CO_2: 370 vs. 550 ppm	Not reported	↑ 15% (eCO_2), chickpea	92
USA	OTC	CO_2: 385 vs. 565 ppm 4 cultivars, common bean	Not reported	↑ 17% (eCO_2) overall for common bean, large variation by cultivar	93
USA	OTC	CO_2: 350 vs. 700 ppm Temperature: ambient vs. range 28–40°C day and 18–30°C night	Not reported	↑ 22% (eCO_2) common bean ↓ 30–100% (eCO_2 + eT) common bean	94

[1] eCO_2, elevated carbon dioxide; eT, elevated temperature; FACE, free-air carbon dioxide enrichment; HD, Hei-maodou; OTC, open-top container; T-FACE, temperature free-air carbon dioxide enrichment; ZK, Zhongke-maodou; arrow up denotes increase, arrow down denotes decrease, arrow side-to-side denotes no change.

TABLE 4 Effect of elevated carbon dioxide, elevated temperature, and other conditions on the zinc, iron, and carotenoids content and yield of fruit and vegetables[1]

Location	Type	Crop	Conditions	Micronutrients	Yield	Reference
Japan	Semi-closed chamber	Mustard spinach, bok choy	CO_2: 390 vs. 700 ppm	Zn ↓ 20% (eCO_2) Fe ↓ 20% (eCO_2)	Not reported	45
China	OTC	Cucumber	CO_2: 400 vs. 800 or 1200 ppm Soil: low or high N	Zn ↑ 16% (eCO_2 800 ppm) low N Fe ↓ 14% (eCO_2 800 ppm) low N Zn ↓ 14% (eCO_2 800 ppm) high N Fe ↓ 15% (eCO_2 800 ppm) high N Zn ↑ 30% (eCO_2 1200 ppm) low N Fe ↓ 17% (eCO_2 1200 ppm) low N Zn ↓ 12% (eCO_2 1200 ppm) high N Fe ↓ 34% (eCO_2 1200 ppm) high N	↑ 36% (eCO_2 800 ppm) low N ↑ 34% (eCO_2 800 ppm) low N ↑ 107% (eCO_2 1200 ppm) high N ↑ 71% (eCO_2 1200 ppm) high N	97
Australia	Growth chamber	Strawberry (Albion, San Andreas cultivars)	CO_2: 400 vs. 650, 950 ppm Temperature: 25°C vs. 30°C	Not reported	↑ 12% (eCO_2 650 ppm + eT), Albion ↓ 49% (eCO_2 950 ppm + eT), Albion ↓ 56% (eCO_2 650 ppm + eT), San Andreas ↓ 50% (eCO_2 950 ppm + eT), San Andreas	98
China	OTC	Cucumber	CO_2: 400 vs. 625 or 1200 ppm Soil: low, medium, or high N	Zn ↓ 63% (eCO_2) low N Fe ↓ 57% (eCO_2) low N Zn ↓ 15% (eCO_2) medium N Fe ↓ 33% (eCO_2) medium N Zn ↓ 25% (eCO_2) high N Fe ↓ 3% (eCO_2) high N	Not reported	99
Spain	Greenhouse	Sweet pepper	CO_2: 380 vs. 800 ppm Soil: nitrate vs. ammonium nitrate	Lycopene ↔ (eCO_2) β-Carotene ↔ (eCO_2) Zn ↔ (eCO_2) Fe ↓ 13% (eCO_2)	Not reported	100
Netherlands	Climate-controlled room	Chinese cabbage	CO_2: 420 vs. 800 ppm Temperature: 15°C day and 12°C night vs. 21°C day and 18°C night Soil: nitrate vs. ammonium nitrate	Zn ↓ 18% (eCO_2) nitrate Zn ↔ (eCO_2) ammonium nitrate Zn ↔ (eCO_2 + eT) nitrate Zn ↔ (eCO_2 + eT) ammonium nitrate Fe ↔ (eCO_2) nitrate Fe ↔ (eCO_2) ammonium nitrate Fe ↔ (eCO_2 + eT) nitrate Fe ↔ (eCO_2 + eT) ammonium nitrate	Not reported	101
USA	Growth chamber	Lettuce, spinach	CO_2: 400 vs. 700 ppm	Zn ↓ 29% (eCO_2) lettuce Zn ↓ 18% (eCO_2) spinach Fe ↔ (eCO_2) lettuce Fe ↓ 30% (eCO_2) spinach	Not reported	102
Spain	Growth chamber	Lettuce, (green and red cultivars)	CO_2: 400 vs. 700 ppm	Zn ↔ (eCO_2) green lettuce Zn ↔ (eCO_2) red lettuce Fe ↓ 55% (eCO_2) green lettuce Fe ↓ 40% (eCO_2) red lettuce Carotenoids ~↓ 6% (eCO_2) green lettuce Carotenoids ↔ (eCO_2) red lettuce	Not reported	103

(Continued)

TABLE 4 (*Continued*)

Location	Type	Crop	Conditions	Micronutrients	Yield	Reference
India	OTC	Potato	CO_2: 382 vs. 570 ppm O_3: 50 (ambient) vs. 70 ppb	Zn ↓ 2% (eCO_2) Fe ↓ 25% (eCO_2) Zn ↓ 15% (eCO_2 + eO_3) Fe ↓ 11% (eCO_2 + eO_3)	↑ 92% (eCO_2) ↑ 69% (eCO_2 + eO_3)	104
India	OTC	Spinach	CO_2: 382 vs. 570 ppm O_3: 50 (ambient) vs. 70 ppb	Carotenoids ↔ (eCO_2) Carotenoids ↑ 70% (eCO_2 + eO_3) Carotenoids ↓ 55% (eO_3)	↑ 73% (eCO_2) ↓ 25% (eO_3) ↑ 16% (eCO_2 + eO_3)	105
Pakistan	Greenhouse	Carrot, radish, turnip	CO_2: 400 vs. 1000 ppm	Zn ↓ 17% (eCO_2) carrot Fe ↓ 8% (eCO_2) carrot Zn ↓ 17% (eCO_2) radish Fe ↑ 3% (eCO_2) radish Zn ↓ 15% (eCO_2) turnip Fe ↓ 19% (eCO_2) turnip	↑ 69% (eCO_2) carrot ↑ 139% (eCO_2) radish ↑ 72% (eCO_2) turnip	106
Pakistan	Greenhouse	Tomato (Astra and Eureka cultivars)	CO_2: 400 vs. 1000 ppm	Zn ↓ 14% (eCO_2) Astra Fe ↑ 3% (eCO_2) Astra Zn ↓ 28% (eCO_2) Eureka Fe ↑ 13% (eCO_2) Eureka	↑ 74% (eCO_2) Astra ↑ 84% (eCO_2) Eureka	107
Spain	Greenhouse	Lettuce (red-green cultivars)	CO_2: 395 vs. 710 ppm Soil: with or without arbuscular mycorrhizal fungi (AMF)	Zn ↑ 40% (eCO_2) no AMF, red outer leaves Zn ↑ 19% (eCO_2) no AMF, red inner leaves Zn ↑ 84% (eCO_2) with AMF, red outer leaves Zn ↑ 3% (eCO_2) with AMF, red inner leaves Fe ↑ 510% (eCO_2) no AMF, red outer leaves Fe ↓ 23% (eCO_2) no AMF, red inner leaves Fe ↑ 548% (eCO_2) with AMF, red outer leaves Fe ↑ 148% (eCO_2) with AMF, red inner leaves Zn ↓ 46% (eCO_2) no AMF, green outer leaves Zn ↓ 19% (eCO_2) no AMF, green inner leaves Zn ↑ 16% (eCO_2) with AMF green outer leaves Zn ↓ 33% (eCO_2) with AMF green inner leaves Fe ↑ 758% (eCO_2) no AMF, green outer leaves Fe ↑ 309% (eCO_2) no AMF, green inner leaves Fe ↑ 2% (eCO_2) with AMF green outer leaves Fe ↓ 48% (eCO_2) with AMF green inner leaves Carotenoids ↓ ~40% (eCO_2) no AMF, red outer leaves Carotenoids, ↓ ~16% (eCO_2) no AMF, red inner leaves Carotenoids ↓ ~18% (eCO_2) with AMF, red outer leaves Carotenoids ↓ ~24% (eCO_2) with AMF, red inner leaves Carotenoids ↓ ~7% (eCO_2) no AMF, green outer leaves Carotenoids ↓ ~9% (eCO_2) no AMF, green inner leaves Carotenoids ↓ ~55% (eCO_2) with AMF, green outer leavesCarotenoids ↓ ~22% (eCO_2) with AMF, green inner leaves	Not reported	108
Germany	OTC	Potato	CO_2: 380 vs. 550 ppm	Zn ↔ (eCO_2) Fe ↔ (eCO_2)	Not reported	109
India	OTC	Spinach, fenugreek	CO_2: 350 vs. 600 ppm	Fe ↓ 55% (eCO_2) spinach Fe ↓ 38% (eCO_2) fenugreek	Not reported	110

(*Continued*)

TABLE 4 (*Continued*)

Location	Type	Crop	Conditions	Micronutrients	Yield	Reference
Canada	Growth chamber	Canola	CO_2: 370 vs. 740 ppm Temperature: 22°C day and 18°C night vs. 28°C day and 14°C night Soil: watered vs. drought	Carotenoids ↓ ~8% (eCO_2) watered Carotenoids ↑ ~17% (eCO_2) drought Carotenoids ↔ (eCO_2 + eT) watered Carotenoids ↔ (eCO_2 + eT) drought	Not reported	111
Norway	Field chamber	Onion, carrot, lettuce, parsley, leek, Chinese cabbage, celery, celery root	CO_2: 350 vs. 850 ppm	Not reported	↑ ~23% (eCO_2) onion ↑ ~8% (eCO_2) carrot ↑ ~18% (eCO_2) lettuce ↑ ~17% (eCO_2) parsley ↔ (eCO_2) leek ↔ (eCO_2) Chinese cabbage ↔ (eCO_2) celery ↔ (eCO_2) celery root	112
USA	Growth chamber	Sweet potato	CO_2: 354 vs. 431, 506, 659 ppm	Carotenoids ↔ (eCO_2 431 ppm) Carotenoids ↔ (eCO_2 506 ppm) Carotenoids ↓ 24%, (eCO_2 649 ppm)	Not reported	113

[1]AMF, arbuscular mycorrhizal fungi; eCO_2, elevated carbon dioxide; eO_3, elevated ozone; eT, elevated temperature; FACE, free-air carbon dioxide enrichment; OTC, open-top container; T-FACE, temperature free-air carbon dioxide enrichment; arrow up denotes increase, arrow down denotes decrease, arrow side-to-side denotes no change.

effect on the zinc content of rice (54), reduced the zinc and iron content of potato (104), and increased the carotenoid content of spinach (105). The impact of ozone on crop yields is more well established. Current levels of ground-level ozone are already causing yield loss in major food crops. In a meta-analysis that compared the yield of 6 major food crops grown at ozone levels of ≤26 ppb compared with the current 31–50 ppb, elevated ozone reduced the yield of rice, wheat, and barley by 17.5%, 9.7%, and 8.9%, respectively (128). Elevated ozone reduced the yield of soybean, common bean, and potato by 7.7%, 19%, and 5.3%, respectively (128). Elevated ozone threatens the food supply in the Indo Gangetic Plain of South Asia and the eastern coastal region of China (124). In a study that modeled global data on ozone and wheat production, elevated ground-level ozone reduced wheat yields by an estimated 9.9% in the Northern Hemisphere and 6.2% in the Southern Hemisphere in 2010–2012 (129). In China, during 2015–2018, elevated ground-level ozone concentrations reduced the production of winter wheat by an estimated 20–33%, maize by 5–6%, and rice by 4–9%, representing a total economic loss of US$23–45 billion (130).

Future changes in crop yields due to elevation in temperature and ground-level ozone conditions have been modeled for 2050 compared with 2000 using the Community Earth System Model (CESM) (131). CESM includes a climate change model to simulate the Earth's system consisting of atmosphere, atmospheric chemistry, ocean, ice, land surface, carbon cycle, and other components (132). The production of wheat, maize, and soybean under the RCP8.5 scenario is projected to have a global decrease while rice production is unchanged in 2050 compared with 2000 (131). Ozone regulation under the RCP4.5 scenario has the potential to reduce the warming impact and increase wheat production in China and the United States, but reduce wheat production in South Asia by up to 40% (131). Under RCP4.5, maize in the United States, Europe, and South America, and soybean in South America, would decrease by 40–50% mostly due to higher and more frequent extreme temperatures regardless of trends in ozone (131). A systematic review showed that a 25% increase in ozone was associated with an 8.9% reduction in the yield of vegetables and legumes (133).

Limitations of crop modeling studies

There is considerable heterogeneity between studies (Supplemental Tables 1–4), which limits the generalizability of the findings from experimental studies of the effects of carbon dioxide, temperature, and other conditions on crop yield and micronutrient content. Major limitations of the agronomic studies have been the lack of standardization in study design, experimental setup, number of replicates, and reporting of results. There are differences in cultivars, soils, and agronomic practices that may limit the generalizability of findings. The field may benefit from establishing standards of study design and reporting to facilitate interpretation and comparison of the results across studies. In addition, power calculations are lacking from nearly all agronomic studies reported in this review.

Pollinator loss

Climate change is associated with the phenological disruption of plant–pollinator mutualisms (134). A recent comprehensive review of the impact of climate change on pollinator decline shows that increasing ambient temperature, extended length of growing season, frequent extreme weather events, and winter weather fluctuations drive the homogenization of pollinator biodiversity, leading to long-term loss of resilience and greater susceptibility to collapses of pollinator communities (135). Rising temperature can cause changes in the development rates of plants such that first flowering comes at a different time than the emergence of their pollinators. Historical modeling shows that global change over the last 120 y degraded the interaction network between flowering plants and their pollinators, leading to a loss of bee species (136). Climate-driven shifts in plant ranges, habitat loss and fragmentation due to land-use changes, and high use of pesticides have further reduced pollinator populations (134, 137). Large declines in bumble bee populations have been recorded in North America and Europe (138). The global expansion of agricultural monoculture is associated with a limited pollinator supply and reduced pollination (139).

Of 150 of the world's leading crops, the proportions of vitamin C, vitamin A, folate, and iron in the food supply that are estimated to come from animal-pollinated crop plants are 98%, 70%, 55%, and 29%, respectively (140). The top pollinator-dependent crops that are sources of vitamin A include carrot, sweet potato, spinach, pumpkin, melon, and mango in many areas where vitamin A deficiency is highly prevalent, and in specific regions, such as okra in India; tropical fruits such as guava, jackfruit, passionfruit in India and Thailand; apricot and sour cherry in Iran; and peach in Mexico (141). A modeling analysis of food supplies and 156 countries suggests that complete removal of pollinators would cause a global decrease in the supply of fruit, vegetables, and nuts and seeds by 22.9%, 16.3%, and 22.1%, respectively (142). There would be a large decline in the vitamin A supply, with 71 million people in low-income countries becoming newly deficient in vitamin A (142).

Extreme weather events

Climate change is leading to the increased frequency, magnitude, and duration of extreme weather events such as drought, tropical cyclones, and heat waves (143). The risk of drought is predicted to increase for the entire African continent, with greater severity in central African countries (144). Climate change is predicted to increase the frequency of high-intensity tropical cyclones, with the most damage in North America, East Asia, and the Caribbean–Central American region (145). Extreme weather events can adversely impact agriculture. High groundwater levels in river flows can persist, increasing the susceptibility of flooding with later storms (143). Reduction in soil moisture can amplify the effects of heat waves (143). Extreme weather events have direct impacts upon agriculture and global food production, disrupt the food supply chain, and reduce the access to food (146).

Rising sea level and crops

Rising sea level has great potential to alter coastal ecosystems and destroy productive agricultural land. Ice sheets or glaciers cover ~10% of the Earth's surface and are affected by climate change (19). The Greenland ice sheet and the ice sheets of Antarctica contain enough water to raise global mean sea level (GMSL) by 7.4 m (147) and 58 m (148), respectively. Glaciers, exclusive of Greenland and Antarctica, cover ~706,000 km^2 worldwide and have the potential to raise GMSL by 0.4 m (149). The ocean contains 97% of water on Earth and currently covers 71% of the Earth's surface (19).

Surface air temperature is projected to increase at the average rate of 0.3°C per decade (19). Atmospheric warming is the main driver of glacier recession and ice sheet loss worldwide (19). GMSL is rising and accelerating from 1.4 mm/y in 1901–1990, to 2.1 mm/y in 1993–2015, and to 3.6 mm/y in 2006–2015 (19). The dominant source of GMSL is the sum of melt water from glaciers and the Greenland and Antarctic ice sheets. Between 1992 and 2018, Greenland has lost 3800 billion tons of ice (150). Satellite observations show that, from 1992 to 2017, the Antarctic ice sheet lost 2720 billion tons of ice, raising mean sea level by 7.6 mm (151). Mountain glaciers have lost ~250 billion tons of ice per year between 1901 and 2009, or a loss of 21% of the glaciated volume of glaciers worldwide, excluding Antarctica (152). GMSL has risen by 0.43 to 0.84 m by 2010 relative to 1986–2005 (19). Sea-level rise by the end of the century is projected to be faster under all RCP emissions scenarios, including those compatible with the temperature goal of the Paris Agreement (19). Extreme sea-level events (episodic coastal inundations caused by a combination of high tides, waves, and storm surges) that are historically rare are expected to become commonplace by 2100 (19).

Sea-level rise has the greatest impact on the low elevation coastal zone (LECZ), defined as the contiguous and hydrologically connected zone of land along the coast and below 10 m of elevation. The LECZ comprises 2.3% of the total land area of all coastal countries (153). Currently, ~680 million people, or 10% of the 2010 global population, inhabit the LECZ, and this population is projected to reach >1 billion people by 2050 (19). The populations in the LECZ with the greatest exposure to sea-level rise are mostly in low-income countries (154). The countries with the largest number of rural poor in the LECZ are India, Bangladesh, Myanmar, Cambodia, Nigeria, Pakistan, Iraq, Mozambique, Senegal, Brazil, China, Indonesia, the Philippines, Vietnam, and Thailand (154).

Rising sea level alters coastal ecosystems, agriculture, and the habitability of coastal communities. Erosion, flooding, and salinization accompany rising sea level in low-lying coastal areas. Sea water intrusion is a major cause of salinization and soil degradation. Rice production in coastal areas is especially susceptible to rising sea level and increasing soil salinity (155, 156). Sea-level rise is predicted to reduce global rice production by 1.6% to 2.7% accompanied by global rice price increases of 7.1% to 12.8% by 2080 (157). Rice production in Bangladesh, Japan, Taiwan, Egypt, Myanmar, and Vietnam is especially vulnerable to sea-level rise (157).

Impact of climate change on fisheries

Marine fish are rich in micronutrients and have been suggested as a potential solution to prevent micronutrient deficiencies in coastal populations of LMICs (158). Realizing such potential in the face of degradation of fisheries and climate change may be a challenge. Global fisheries peaked at 130 million tons in 1996 and have been steadily declining since that time (159). Ocean warming and declining oxygen levels in ocean and coastal waters are having an adverse impact upon global fisheries and shifting viable habitats and species ranges (160, 161). Industrial fishing is dominated by wealthy countries (162). Fishing fleets from the European Union, Russia, and East Asia, which have paid for access to fish in the exclusive economic zone (EEZ) of poorer countries, have led to local fish scarcity (163). In addition, countries such as China have built industrial fish meal–processing plants that convert local fresh fish primarily into animal feed (163). If the decline in the marine fish supply continues, an estimated 845 million people, or an additional 11% of the current global population, will become deficient in micronutrients such as zinc, iron, and vitamin A (164).

Another potential consequence of climate change is an adverse effect upon local coastal fisheries in low-income countries. Coral reefs are found in at least 150,000 km of coastline in >100 countries (19). Coral reefs are an important source of fish for poor communities relying upon small-scale, artisanal, or subsistence fishing. Worldwide, there are an estimated 6 million reef fishers in 99 countries and territories with coral reefs (7). Sea-level rise is predicted to elevate water depths beyond the vertical growth capacity of coral reefs, thus jeopardizing local fish supplies for coastal communities (165). Mangrove forests cover 138,000 to 152,000 km^2 in tropical and subtropical coasts of ~120 countries (19) and provide an ecosystem that supports near-shore subsistence, artisanal, and small-scale commercial fisheries (9). There are an estimated 4.1 million mangrove-associated fishers locally, with the highest number found in Indonesia, India, Bangladesh, Myanmar, and Brazil (9). Large-scale mortality of mangroves has occurred since the 1960s, with ~70% of reported mangrove loss from natural causes occurring due to low-frequency, high-intensity weather events such as heat waves and tropical cyclones (166). Satellite mapping shows that natural causes, such as extreme weather, are currently a greater driver than human causes, such as farming and aquaculture, in causing mangrove loss (167). Sea-level rise is altering the distribution of mangroves inland and poleward (19). Small-scale fisheries that rely upon mangroves are important in providing protein and micronutrients to local populations, and degradation of mangrove-associated fisheries may jeopardize this dietary source of micronutrients.

Inland capture fisheries and aquaculture contribute >40% to global finfish production (168). The total inland fisheries catch was 11.5 million tons in 2015, or >12% of global capture fishery production (169). Most of this catch comes from LMICs in Africa and Asia; a large proportion of these fish are destined for local human consumption and are an important source of micronutrients for developing world populations (8). Climate change and freshwater warming are predicted to alter freshwater ecosystems, including species composition, number, and geographic range (169). Freshwater ecosystems are sensitive to climate-related shocks and variability (169). A vulnerability assessment of Africa's freshwater fishes showed that nearly 40% of fish species were vulnerable to climate change due to the highly specialized habitat and life-cycle requirements, especially in the African rift valley lakes, the Congo River drainage, and coastal rivers of West Africa (170).

Animal agriculture and climate change

Meat consumption is projected to increase in LMICs due to large population sizes, high population growth rates, and rising incomes (171). Global consumption of meat is expected to grow between 2020 and 2029 by 12%, with developing regions accounting for ~80% of the growth in meat production (171). Meat production is a major source of GHG emissions, water use, and deforestation (172–174). In addition, arable land that produces plant foods for human consumption is converted to produce animal feed (175). Some LMICs are adopting the industrial food animal production (IFAP) model, which requires intensive use of feed and water (176). In some countries with scarce resources, IFAP may be reducing food security by producing grains for animal feed rather than humans (176). Meat can contribute micronutrients such as iron, zinc, and vitamin B-12 to the diet, but health and environmental concerns have been raised about excessive consumption of meat if LMICs adopt the dietary pattern of industrialized countries (177).

Mitigation and adaptation strategies

The most fundamental mitigation strategy to prevent declines in crop yields and ensure food security is to reduce GHG emissions, the main driver of climate change (19). Short of this goal, which requires international cooperation and compliance, a variety of adaptive strategies have been proposed to improve the micronutrient quality of plants or increase crop yields in the face of climate change. Iron and zinc biofortification of rice may be achieved through agronomic practices such as applying zinc or iron to soil or foliage (178–180). Plant-breeding approaches, whether conventional breeding approaches or genetic engineering, may be used to obtain higher zinc and iron concentrations in rice (178, 179, 181). Challenges to zinc fortification of rice include low uptake, transport, and loading of zinc into the rice grain (182). Both rice and wheat have extremely low iron concentrations, and most iron is present mainly in the outer

TABLE 5 Potential impacts of climate change on food sources of micronutrients

Climate change factor	Biological consequences	Impact on food sources of micronutrients
Increasing carbon dioxide and rising temperature combined	Reduced photosynthesis Altered plant mineral metabolism Loss of suitable growing region	Decreased yield of rice, wheat, barley, legumes, vegetables, fruits, nuts
Ground-level ozone	Reduced photosynthesis Altered plant mineral metabolism	Reduced yield of rice, wheat, barley, corn, legumes, potato
Increased extreme weather events	Water scarcity Water excess Wind damage Soil loss	Reduced yield of crops Loss of crops
Pollinator loss	Reduced pollination	Reduced yield of pollinator-dependent crops: fruits, vegetables, nuts
Sea-level rise	Coastal inundation Salt intrusion Coral reef loss Mangrove loss	Loss of coastal rice production Loss of coastal fisheries
Ocean warming and declining oxygen	Shifts in range of fish Decline in suitable habitat	Reduced ocean fisheries catch
Freshwater warming	Altered freshwater ecosystems Decline in suitable habitat	Reduced inland fisheries catch

bran layers (183). Conventional breeding may be difficult as an approach to increase iron in rice or wheat, since iron-rich rice and wheat germplasms are not available (183). Iron and zinc biofortification of wheat is also being developed using fertilizers and plant breeding (59, 184). Stable isotope studies show that zinc absorption from agronomically biofortified wheat is similar to post-harvest fortified wheat in humans (185). Plant-breeding approaches have been proposed to make legumes more resistant to elevated temperatures using insights from proteomic studies (37).

Climate change is altering environmental factors that affect both the geographical range of plants and growing season. Adaptive approaches to ensure crop productivity include shifting the location and elevation where crops are grown and increasing the length of the growing season where possible (186). The adverse impact of ozone upon rice and wheat yields may be countered by breeding plants that are more ozone-resistant (129, 187, 188). Similarly, the development of rice cultivars that are more salt tolerant may help adapt to salt intrusion in areas of coastal rice production (189). Policy changes are needed to ensure sustainability and better management of marine fisheries (162). Countries that have coastal fisheries that provide an important source of micronutrients for populations in LMICs could enact more protective legislation to regulate foreign fleets in their EEZ (163). Greater efforts could be taken to protect inland fisheries from competition with other water uses (168). The characterization of sustainable healthy diets, defined by FAO and WHO as "dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable" (190), with low to modest amounts of animal-source foods may help limit GHGs and other environmental impacts of animal agriculture in LMICs (191). The development of crops that are adapted to climate change may take a considerable amount of time and investment. More immediate approaches such as national micronutrient supplementation programs, post-harvest fortification of staple foods, and initiatives to increase dietary diversity and promote micronutrient-rich foods are a major priority.

Conclusions

Climate change has great potential to increase the risk of micronutrient malnutrition in vulnerable populations through many different pathways (Figure 1), with impacts as summarized in **Table 5**. The combination of increasing atmospheric carbon dioxide and rising temperature is predicted to reduce the overall yield of major staple crops, fruits, vegetables, and nuts, rather than affect the micronutrient content of the foods themselves. In addition, the yield of crops is reduced by increased ground-level ozone and an increase in extreme weather events. Pollinator loss is expected to reduce the yield of many pollinator-dependent crops such as fruits, vegetables, and nuts. Sea-level rise resulting from melting of ice sheets and glaciers is predicted to result in coastal inundation, salt intrusion, and loss of coral reefs and mangrove forests, with an adverse impact upon coastal rice production and coastal fisheries. Global ocean fisheries catch is predicted to decline because of ocean warming and declining oxygen. Freshwater warming is also expected to alter ecosystems and reduce inland fisheries catch. A decrease in the availability of micronutrient-rich foods (i.e., major staple crops, fruits, vegetables, nuts, and fish) may lead to global increases in food prices and increased vulnerability of poor families to micronutrient malnutrition (11, 12, 192). The impacts of climate change on the availability of micronutrient-rich foods are likely to vary by region and capacity for adaptation.

In addition to limiting GHG production, a variety of mitigation strategies will be required to ensure reduction in the risk of micronutrient malnutrition, such as post-harvest fortification of foods; micronutrient supplementation; biofortification of staple crops with zinc and iron; plant breeding or genetic approaches to increase zinc, iron, and provitamin A carotenoid content of plant foods; and developing staple crops that are tolerant of abiotic stressors such as elevated CO_2, elevated temperature, and increased soil salinity.

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