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Culturally appropriate shifts in staple grain consumption can improve multiple sustainability outcomes

To cite this article: Dongyang Wei and Kyle Frankel Davis 2021 *Environ. Res. Lett.* **16** 125006

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RECEIVED
27 July 2021REVISED
18 October 2021ACCEPTED FOR PUBLICATION
25 October 2021PUBLISHED
24 November 2021

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E-mail: dywei@udel.edu**Keywords:** dietary shifts, sustainable diets, C4 crops, whole grains, food securitySupplementary material for this article is available [online](#)**Abstract**

Diets exercise great influence over both human and environmental health. While numerous efforts have sought to define and identify sustainable diets, there remains a poor understanding of the extent to which such shifts are feasible when taking into account local dietary preferences. Accounting for 40% of dietary calories and 46% of global cropland, cereals offer an important food group by which culturally appropriate dietary shifts may achieve large sustainability benefits. Here we combine country-specific information on dietary cereal supply with nutrient content values, CO₂ nutrient penalties, and environmental footprints to quantify the outcomes of adopting two feasible dietary shifts—maximizing the share of C4 cereals (e.g. maize, millet, sorghum) based on historical shares and increasing the share of whole grains. Our results show that increasing the share of whole grains can increase nutrient supply (+7% protein, +37% iron, +42% zinc) and overcome the nutrient-depleting effects of elevated CO₂ (eCO₂) and that maximizing the share of C4 cereals can substantially reduce environmental burden (−12% greenhouse gas emissions, −11% blue water demand), particularly in Africa and the Middle East. We also find that a combination of the two strategies would likely produce strong co-benefits between increased nutrient supply and reduced environmental impacts with mixed outcomes for offsetting the effects of eCO₂. Such simultaneous improvements are particularly important for food insecure regions such as West Africa and Southeast Asia. These findings demonstrate important opportunities to identify sustainable diets that incorporate local preferences and cultural acceptability. Such considerations are essential when developing demand-side solutions to achieve more sustainable food systems.

1. Introduction

Global food production has increased markedly since the 1960s [1], tripling to feed a rapidly growing population and avoid widespread hunger [2]. Yet there remains a high prevalence of undernourishment and micronutrient deficiencies in many world regions [3], and agriculture has become one of the most extensive activities by which humanity has modified the planet [4, 5]. In response to the pressing needs to simultaneously increase food supply, improve nutrition, and minimize environmental impacts, multiple investigations have sought to develop holistic solutions to improve the sustainability of food systems [6–9].

One recent conceptualization that offers promise for addressing these multiple challenges is that of planetary health which recognizes that continued improvement in human wellbeing must be accompanied by environmental stewardship [10]. This concept has been applied at both global [11] and national [12] scales to identify diets that may achieve co-benefits for human health and the environment. It has also served as the basis for the EAT-Lancet Commission which sought to identify a universal reference diet to simultaneously meet nutritional requirements, reduce diet-related premature deaths, and reduce environmental impacts of food production [13]. While all of this recent work has made important steps towards

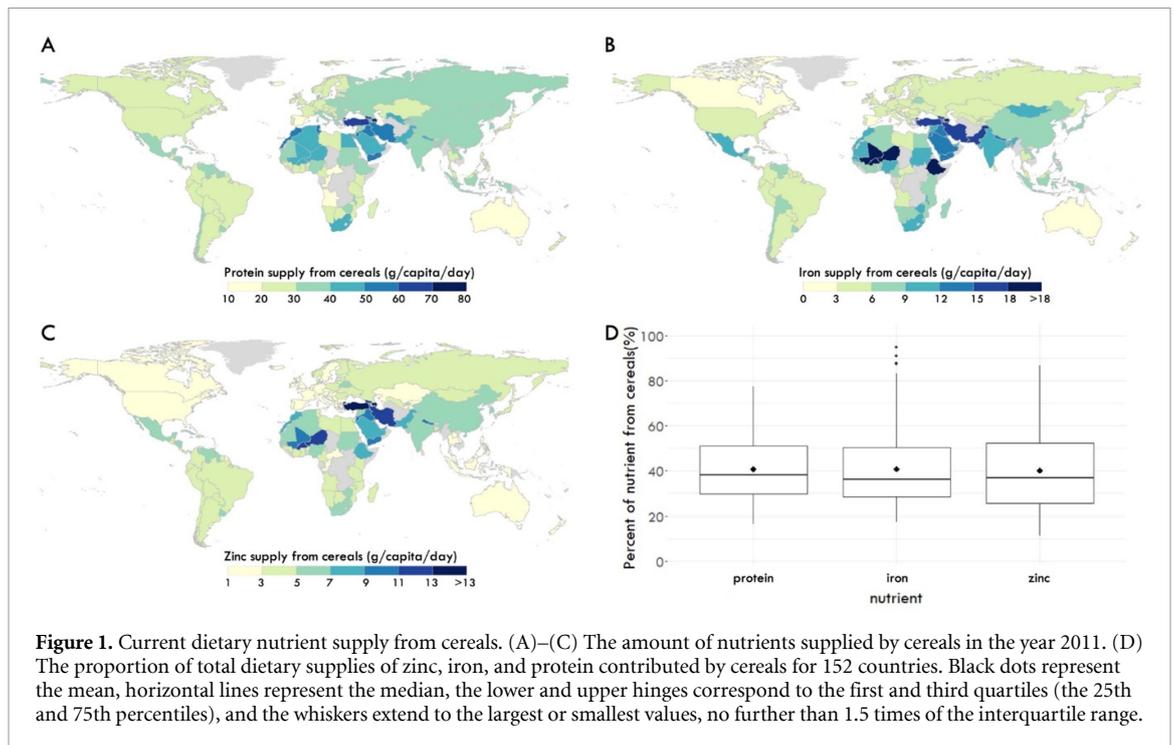


Figure 1. Current dietary nutrient supply from cereals. (A)–(C) The amount of nutrients supplied by cereals in the year 2011. (D) The proportion of total dietary supplies of zinc, iron, and protein contributed by cereals for 152 countries. Black dots represent the mean, horizontal lines represent the median, the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles), and the whiskers extend to the largest or smallest values, no further than 1.5 times of the interquartile range.

aligning the goals of human health and environmental sustainability, developing sustainable diets that are locally feasible and culturally appropriate is an essential component toward ensuring their widespread adoption but is an aspect that has gone largely ignored.

We attempt to address this gap by examining the extent to which country-specific shifts in per capita cereal supply—currently accounting for 40% of dietary calories, protein, iron, and zinc, on average [14] (figure 1)—can contribute to more sustainable diets. While cereals supply a relatively small share of dietary nutrient supply for most other countries, especially for those in the Middle East and Africa. This highlights the important role that modified cereal supply can potentially play in providing healthier and more sustainable diets. Two shifts in particular—increasing shares of C4 cereals and whole grains—have received growing attention as feasible solutions, yet the extent to which each may offer benefits or tradeoffs relative to current dietary patterns remains unclear. Regarding the first potential dietary shift, C4 cereals (e.g. maize, millets, sorghum) employ a photosynthetic pathway that physically separates CO₂ fixation from the biochemical cycle for generating sugars, leaving them generally more water use efficient than C3 cereals (e.g. rice, wheat) [15]. C4 crops also tend to be more nutrient dense [14] and to have lower GHG intensities [16]. Recent experiments have also demonstrated that C4 cereals experience little to no depletion of key dietary nutrients (e.g. protein, iron,

zinc) within their plant tissue under elevated atmospheric CO₂, while C3 cereals can experience reductions between −3.1% and −15.0% for these nutrients [17]. In addition, C4 cereals were much more widely cultivated and consumed decades ago (supplementary table 1 (available online at stacks.iop.org/ERL/16/125006/mmedia)). However, with the onset of the Green Revolution as well as broader economic shifts (e.g. rising incomes), traditional C4 cereals (e.g. millets and sorghum) were gradually replaced by high-yielding C3 cereals (e.g. wheat, rice), shifting supply and consumption toward less nutrient-dense crops [2, 18]. For the second potential dietary shift, whole grains include the entire grain kernel, which contains much of a crop's essential micronutrients and dietary fiber [19]. Recent work has proposed transitioning towards cereal consumption baskets that are comprised of equal parts whole and refined grains to not only improve the acceptability of whole grains but also enhance nutrient availability—through reductions in absorption-inhibiting bran components and with targeted fortification of refined grains [20, 21]. This balance between whole and refined grains can contribute to reduced incidence of non-communicable diseases such as cardiovascular disease and type 2 diabetes [22]. While rising living standards, rapid urbanization, and overall convenience contributed to growing consumption of refined grains in the past, whole grains are seeing a visible rebound in consumption due to enhanced advocacy, awareness and promotion. Whole grains are beginning to comprise a larger fraction of cereal consumption and are of growing popularity in many regions in

recent years [23, 24], indicating that their increased incorporation into diets may be realistic as a result of cultural memory and social momentum. However, for both of these potential shifts in dietary cereal supply, a global assessment of their potential co-benefits or trade-offs across multiple dimensions of sustainability is still needed, and it remains unclear how the outcomes of these interventions may differ between countries when accounting for their local feasibility.

Here we quantify the country-specific outcomes of current cereal supply—in terms of dietary nutrient supply, nutrient content losses under elevated CO₂ (eCO₂), water demand, and GHG emissions—and evaluate the potential for two promising and feasible dietary shifts—increasing shares of C4 cereals and whole grains—to realize co-benefits or tradeoffs between these dimensions. To do so, we first combine country- and crop-specific data on current per capita cereal supply with information on crop nutrient content [14], crop-specific footprints for GHG emissions intensities [16], and blue (irrigation) water footprints [25] to estimate current supplies of protein, iron, and zinc from cereals and the associated GHG emissions and blue water demand of their production. We also utilize known relationships between atmospheric CO₂ concentrations and crop nutrient content to estimate the nutrient losses that current per capita cereal supply would incur under eCO₂. Holding per capita calorie supply from cereals constant, we then implement three dietary shift scenarios to: (a) maximize the proportion of C4 grains in current cereal consumption—based on the maximum historical (1961–2011) share of C4 grains in each country's diet; (b) ensure that at least half of dietary cereal supply is comprised of whole grains—based on available data for wheat, maize, sorghum, and millet; and (c) combine shifts towards greater shares of both C4 cereals and whole grains. Finally, we quantify the outcomes of these dietary shifts across multiple dimensions and evaluate their co-benefits or tradeoffs relative to current cereal consumption. In doing so, we assess where and to what extent these interventions might improve the sustainability of diets in a feasible and culturally appropriate manner—a key consideration in achieving more sustainable food systems overall.

2. Materials and methods

2.1. Data

Historical data on per capita cereal supply for the years 1961 through 2011 came from the global expanded nutrient supply (GENuS) database [14]. The GENuS database is an expansion of FAO Food Balance Sheets [1], containing information on the edible weight of food supply for 225 food commodities. These data currently cover 152 countries and 96% of the world's population. The GENuS database provides six national or regional nutrient

composition tables for 23 nutrients. We considered 16 of the 18 reported staple cereals (table 1) to calculate their dietary supply of calories, protein, iron, and zinc. 'Fonio' and 'Canary Seed' were omitted as there was no reported dietary supply for any country. Whole grains are defined in the GENuS database as 'unprocessed grain', including whole grain and whole-grain flour that contains bran and germ. For this study, we consider all forms of cereal without bran and germ as having undergone some degree of processing and therefore as refined grains, labeling them with the term 'flour' (i.e. wheat flour, corn flour, millet flour, sorghum flour). Data for whole and refined grains covers wheat, maize, sorghum, and millet. Rice was not divided into whole or refined grains in the GENuS database, as most rice supply is assumed to be milled (i.e. polished).

Data on the effect of eCO₂ (541 ppm; RCP 8.5 in the year 2050) on staple crop nutrient content (protein, iron, and zinc) came from Myers *et al* [17]. Following Beach *et al* [26], we assigned these carbon nutrition penalty data to the 16 study crops (supplementary table 2). The difference between Beach *et al* [26] and our classification is we assume no effect on 'C4-grass' (i.e. C4 crops except maize), as the effect of eCO₂ on C4-grass is either insignificant or not available in the original experimental data [17].

Crop-specific information on GHG emission intensities (g CO₂e (kcal)⁻¹) for different crops were taken from Carlson *et al* [16]. We assume that refined grains have the same GHG intensity as their corresponding whole grains. While GHG emissions may be allocated to refined grains and their coproducts (e.g. bran and germ) to further refine our estimates (see e.g. Kim *et al* [27]), we expect that such allocations would produce only minor differences from our findings. This likely makes our estimates of GHG emission reductions conservative, as this ignores GHG emissions generated during processing and refinement. Crop-specific blue water footprint data (i.e. the volume of irrigation water consumed per unit of crop) (m³ H₂O tonne⁻¹) came from Mekonnen and Hoekstra [25]. The blue water footprint values for 'sorghum' and 'millet' were used for 'sorghum flour' and 'millet flour'. All values are listed in supplementary table 3.

2.2. Dietary transitions

Dietary scenarios were enacted at the country-level to account for each nation's current and historical dietary patterns, thereby better ensuring culturally appropriate and locally acceptable shifts.

2.2.1. Current dietary cereal supply

Current per capita cereal supply for 16 cereals and 152 countries corresponded to the year 2011, the most recent year available in the GENuS database. This current dietary cereal supply served as the basis for the dietary transitions performed in this study.

Table 1. Global average nutrient content of study crops. Average values were weighted by the total population under each regional composition table.

Crop name	C3 or C4	Calorie (kcal/100 g)	Protein (g/100 g)	Iron (mg/100 g)	Zinc (mg/100 g)
Wheat	C3	339	12.35	4.40	2.33
Wheat flour	C3	354	10.80	2.31	1.17
Rice (milled equivalent)	C3	351	7.03	1.45	1.20
Barley	C3	345	9.83	5.21	2.27
Rye	C3	338	10.15	2.38	2.65
Oats	C3	377	14.45	6.88	3.42
Buckwheat	C3	332	11.62	5.84	2.73
Triticale	C3	336	13.05	2.57	3.45
Quinoa	C3	369	11.70	5.20	3.10
Maize	C4	353	9.39	2.50	2.13
Corn flour	C4	361	7.05	1.67	0.87
Millet	C4	354	11.09	4.59	2.11
Millet flour	C4	379	10.35	4.16	2.66
Sorghum	C4	343	11.33	4.99	1.93
Sorghum flour	C4	356	10.57	1.40	0.71
Cereals; nes	C4	341	9.60	48.80	3.63

2.2.2. Maximizing C4 cereals (max C4)

We categorized the 16 cereals as either C3 or C4 cereals based on physiology. Data for the ‘cereals; nes’ category (a mixture of miscellaneous C3 and C4 cereals) was dropped in all countries except for Ethiopia and Swaziland, where the C4 cereal teff clearly comprised this category and accounts for a considerable proportion of local diets. To identify the highest historical fraction of cereal calories contributed by C4 cereals, we first calculated the country-level ratio ($r_{t,c}$) of total calorie supply from C4 and C3 groups for each year t in country c as:

$$r_{t,c} = \frac{\sum_{c4} (s_{c4,t,c} \times k_{c4,t,c})}{\sum_{c3} (s_{c3,t,c} \times k_{c3,t,c})} \quad (1)$$

where s is the supply of a crop in year t , k is the caloric content (kcal/100 g) of a crop, and the subscripts $c4$ and $c3$ correspond to C4 and C3 crops respectively. The cereal supply composition corresponding to the year ($tmax$) with the highest ratio in country c was then scaled to ensure a calorie supply identical to the current diet. To do so, we adjusted the supply of each cereal by:

$$s_{g,adj,c} = s_{g,tmax,c} \times \frac{\sum_g (s_{g,2011,c} \times k_{g,c})}{\sum_g (s_{g,tmax,c} \times k_{g,c})} \quad (2)$$

where $s_{g,2011,c}$ is the amount of crop g in current diet of country c .

2.2.3. ‘Making half the grains whole’ (half-whole)

Within the GENUs database, the ratios of whole and refined grains are constant for each country-crop across all reported years (e.g. the ratio of whole:refined grain wheat in the US was assumed to be 1:78 over the years 1961–2011) and provided for four cereals (wheat, maize, sorghum, and millet). No

ratios were provided for rice, which we assumed to be fully refined (i.e. milled or polished). For each of the four cereals for which this whole-refined disaggregation was available, we defined the food supply (g/capita/day) of whole grains and refined grains of crop g in current diet in country c as $s_{gw,g,c}$ and $s_{gr,g,c}$. We then adjusted the amount of whole grains ($s'_{gw,g,c}$) and refined grains ($s'_{gr,g,c}$) following:

$$\begin{aligned} \text{If } s_{gw,g,c} \geq s_{gr,g,c}, \text{ then } s'_{gw,g,c} &= s_{gw,g,c}, s'_{gr,g,c} = s_{gr,g,c}; \\ \text{If } s_{gw,g,c} < s_{gr,g,c}, \text{ then } s'_{gw,g,c} &= s'_{gr,g,c} \\ &= (s_{gw,g,c} + s_{gr,g,c})/2. \end{aligned} \quad (3)$$

All the cereal supplies were then scaled using equation (2) to keep total calorie supply constant.

2.2.4. Combination of the two transitions (combo)

The combination of the two dietary shifts was implemented by first identifying the maximum C4/C3 ratio following equation (1) and then adjusting the shares of whole and refined grains for each cereal following equation (3). Finally, all of the cereals were proportionally scaled to match the calorie supplied by cereals in the current diet using equation (2). In all of these scenarios, we note that we evaluate cereal supply instead of consumption (which accounts for food waste), due to data limitations. Given the varying degrees to which each cereal may experience consumer waste, a certain percent change in the supply of a cereal may not necessarily translate to the same percent change in consumption.

2.3. Outcomes

The outcomes of the different dietary transitions were quantified across multiple dimensions.

Per capita supply of nutrient n from in country c was calculated as:

$$ns_{n,c} = \sum_g (s_{g,c} \times ng_{n,c}). \quad (4)$$

Per capita supply of nutrient n under $e\text{CO}_2$ in country c was calculated as:

$$ns_{CO_2n,c} = \sum_g (s_{g,c} \times ng_{g,n,c} \times (1 + p_{j,n}\%)) \quad (5)$$

where ns is the supply of nutrient n in country c , ns_{CO_2} is the supply of nutrient n under $e\text{CO}_2$ in country c , s is the amount (g/capita/day) of crop g in country c under a certain dietary scenario, ng is the nutrient content (g/100 g for protein or mg/100 g for zinc and iron) of nutrient n in crop g in country c , and p is the percent change (%) in nutrient content at $[\text{CO}_2]$ of 541 ppm on nutrient n in crop g .

The footprints for GHG emissions and blue water were calculated as:

$$ghgs_c = \sum_g (s_{g,c} \times k_{g,c}/100 \times ghgg_g) \quad (6)$$

$$bw_c = \sum_g (s_{g,c} \times bwg_g \times 10^{-6}) \quad (7)$$

where $ghgs$ is the greenhouse gas emissions (g $\text{CO}_2\text{e}/\text{capita}/\text{day}$) of the country c , bw is the blue water footprint ($\text{m}^3/\text{capita}/\text{day}$) of the country c , and $ghgg$ and bwg are the global average greenhouse gas emission intensity (g CO_2e (kcal) $^{-1}$) and blue water footprint ($\text{m}^3 \text{ton}^{-1}$) of crop g , respectively. We acknowledge that, for blue water footprints especially, the use of a global-average value for each crop presents limitations as a crop's blue water footprint can vary widely between countries (as has been accounted for in other studies (e.g. Kim *et al* [27]). However, an evaluation of how the sourcing of cereals (e.g. domestic vs internationally) may change in order to support our dietary scenarios is beyond the scope of our analysis, and as such, global-average values represent a cautious and appropriate selection for quantifying broad changes in the sustainability outcomes of dietary shifts.

3. Results

3.1. Nutrient supply

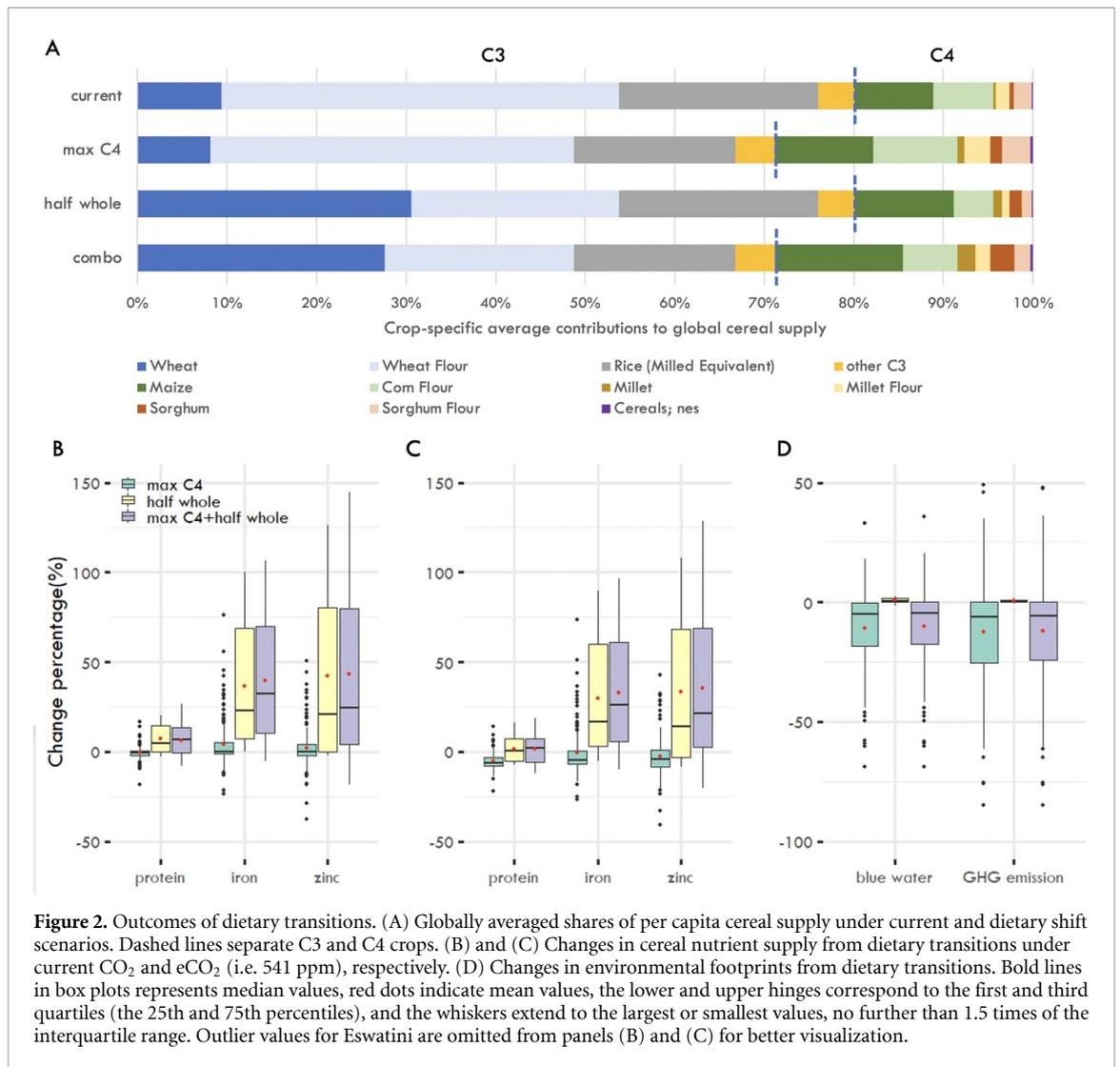
We find that the three dietary shifts that we considered provide different levels of improvements in dietary nutrient supply. For the scenario in which we convert half of all cereal supply to whole grains (hereafter 'half whole'), we see significant improvements in mean global nutrient supply from cereals by +7% (protein) +37% (iron), and +42% (zinc), relative to current diets (figure 2(B) and supplementary figure 1). These gains are mainly attributable to wheat and maize, which are prominent crops in the diets of many countries. We note that due to data limitations we were unable to disaggregate rice supply between refined and whole grains. Because of the important role that rice plays in the cereal mix of many nations' diets, shifts towards increasing shares

of, for example, brown rice in lieu of some polished white rice will likely offer additional gains in nutrient supply. Alternatively, for the scenario to maximize C4 cereals based on local diets (hereafter 'max C4'), we saw an approximately 10% increase in the share of C4 crops (figure 2(A)), which modified the mean global supply of protein, iron, and zinc only modestly -1% , $+4\%$, and $+2\%$, respectively (figure 2(B)). While this indicates a limited effect of increased C4 cereals on nutrient supply globally, we find that larger increases in the share of C4 crops were possible for certain countries (e.g. Uzbekistan, Mauritania, Libya) which led to more substantial nutrient supply increases (protein: $+17\%$, iron: $+76\%$, zinc: $+51\%$ at most) (figure 2(B)). A combination of these two dietary transitions (hereafter 'combo') showed substantial improvements across all nutrients, similar to the 'half whole' scenario.

3.2. CO_2 penalty

We also find that current diets would experience a range of reductions in nutrient supply due to the effects of $e\text{CO}_2$ (figures 3(A)–(C)). We estimate that reductions in iron supply would be relatively modest globally (approximately -5%), a finding consistent with previous work [26]. Zinc and protein supplies will be affected more heterogeneously, with the largest zinc and protein losses expected in countries with diets that rely heavily on C3 cereals (e.g. rice, wheat).

When examining dietary transitions under $e\text{CO}_2$ (figure 2(C)), we find that the 'half whole' scenario experiences substantial reductions in the added nutrient supply which it could provide (e.g. $+37\%$ in mean global iron supply relative to current diets under current CO_2 levels vs $+30\%$ in iron supply under $e\text{CO}_2$) but that the overall large increases in nutrient supply afforded by this shift overcome the impact of $e\text{CO}_2$. Conversely, nutrient supply reductions under the 'max C4' scenario would be more modest (e.g. $+4.3\%$ in iron supply relative to current diets under current CO_2 levels vs -0.6% in iron supply under $e\text{CO}_2$) but would be unable to overcome the $e\text{CO}_2$ impact. This highlights a tradeoff between the two dietary shifts, where increased whole grains lead to large improvements in nutrient supply while increased C4 cereals is more resilient to the effects of $e\text{CO}_2$. Given the different benefits afforded by these two dietary shifts, we then examined where a combination of these two strategies could be used to overcome the effects of $e\text{CO}_2$ on nutrient supply (figures 3(D)–(F)). We find that most countries in Europe, North America, and Oceania could offset the CO_2 penalty through dietary shifts in cereals. Other regions (i.e. Africa, Latin America, East and Southeast Asia) would also see benefits depending on the nutrient of interest. However, dietary shifts in cereals in South Asia and the Middle East would not be sufficient to fully offset $e\text{CO}_2$ effects. This may be due



in part to our exclusion of ‘whole grain’ rice but also suggests that, for some countries, fortification of cereals or dietary shifts to improve intake of other high-nutrient food groups will be necessary to overcome the effects of eCO₂.

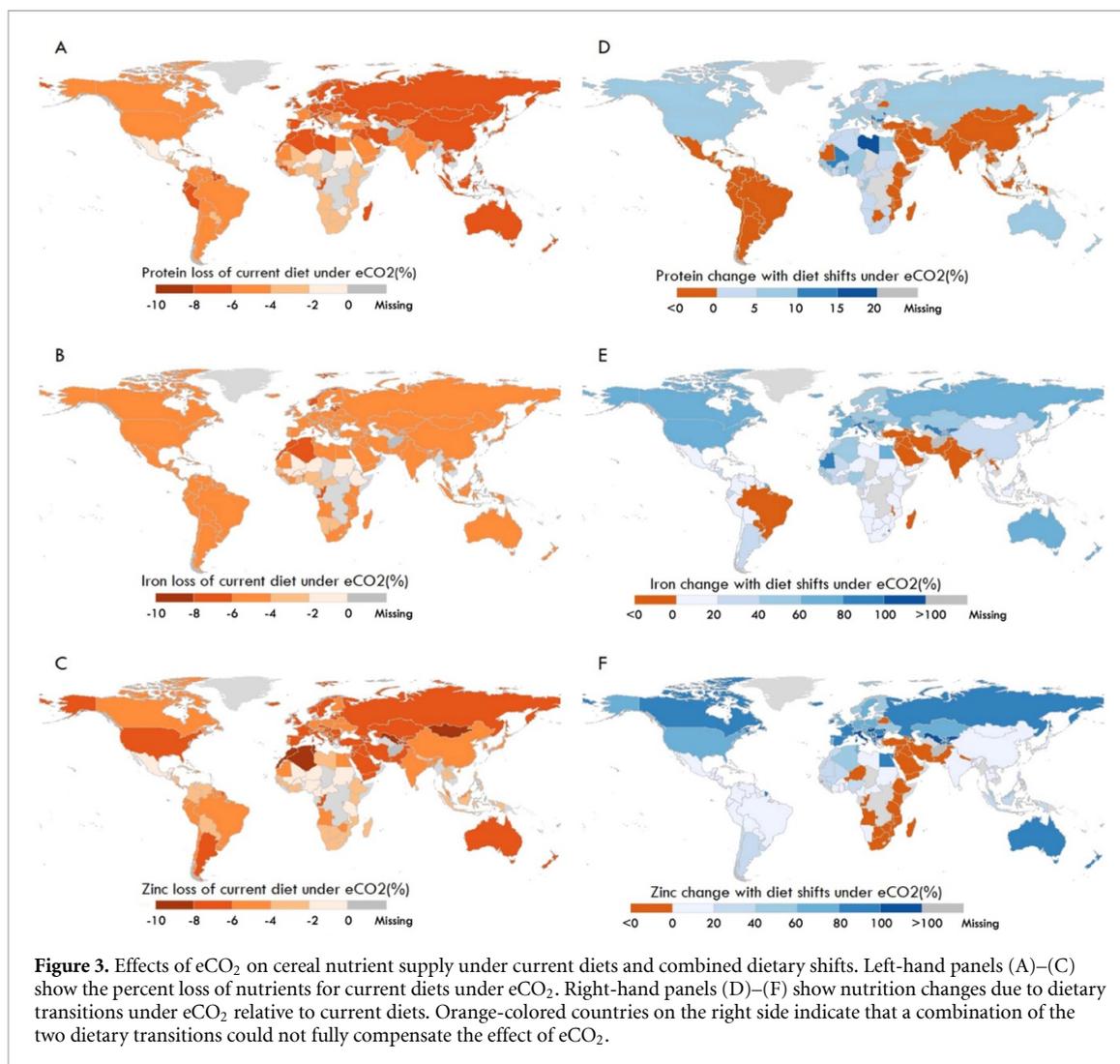
3.3. Environmental footprint

We find that dietary shifts could reduce blue water demand by 11% globally under the ‘max C4’ scenario. Given that approximately 40% of current blue water demand is unsustainable (i.e. where demand exceeds availability) [28], this indicates substantial potential for dietary shifts towards C4 cereals to contribute to the mitigation of water scarcity and unsustainable water use, depending on water availability in the initial locations of production. Certain water-scarce countries (e.g. Yemen, Nigeria) could reduce cereal water demand by up to 60%, providing substantial opportunity to alleviate current water scarcity. Meanwhile, for countries who contribute the largest volumes of unsustainable water demand (e.g.

United State, India, China) [28], shifting to more C4 crops can also lead to considerably less unsustainable water consumption. Similarly for GHG emissions, we estimate that the ‘max C4’ scenario would lead to a 12% reduction globally. In particular, such dietary shifts towards C4 cereals hold great demand-side mitigation potential for top carbon emitters, for instance decreasing GHG emissions associated with China’s cereal demand by 12.2% (35.4 Tg CO₂e/yr) and India’s by 6.1% (14.5 Tg CO₂e/yr) (supplementary table 2). Not surprisingly, we found little change in environmental outcomes under the ‘half whole’ scenario as this shift does not change the crops that constitute the cereal mix within diets.

3.4. Co-benefits and tradeoffs across outcomes

Given the nutritional and eCO₂ benefits afforded by increasing whole grains (i.e. ‘half whole’) and the environmental benefits derived from larger shares of C4 cereals (i.e. ‘max C4’), we then evaluated the potential for co-benefits across all of the study

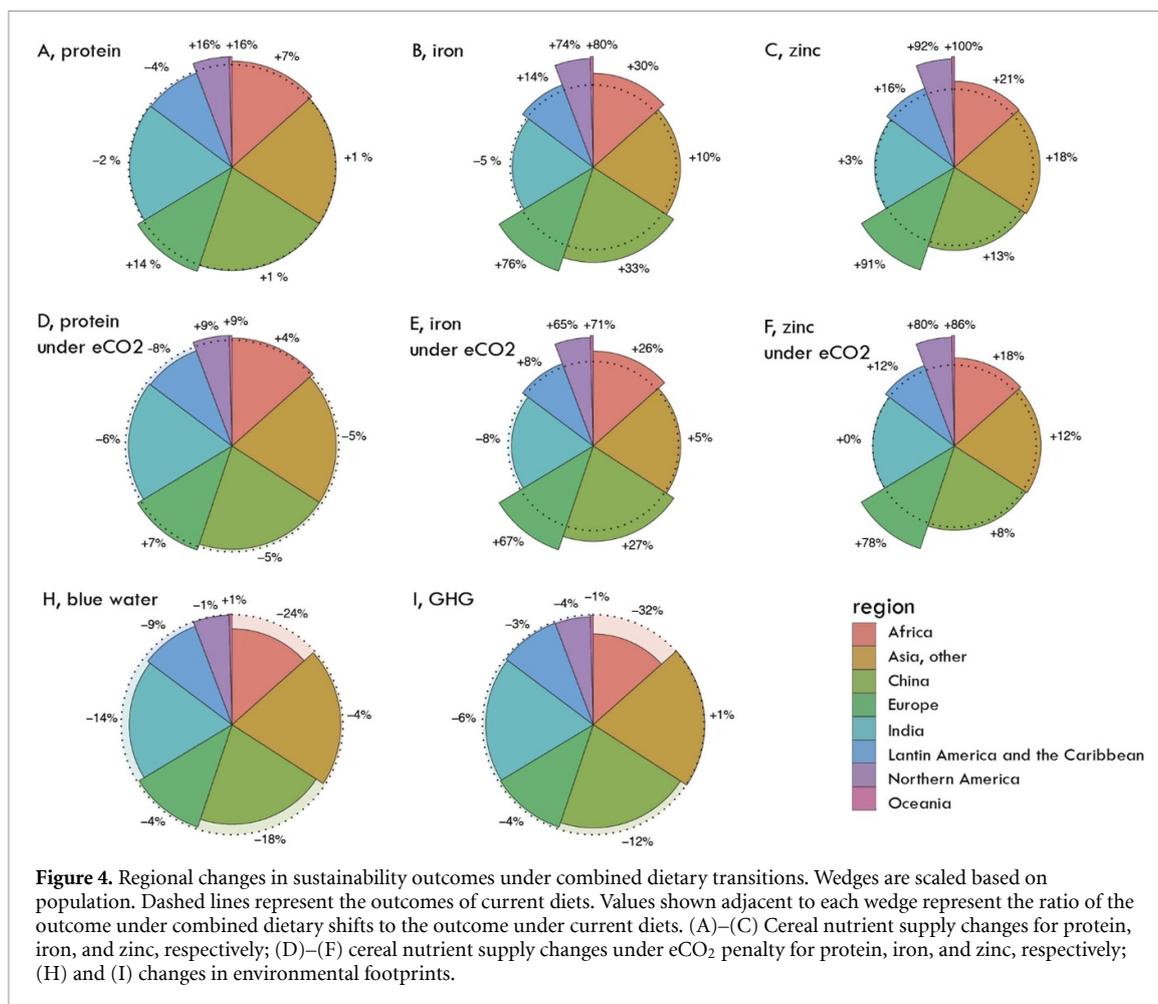


dimensions when the two dietary shifts were combined (figure 4 and supplementary figure 2). We find that nearly all countries would experience benefits for nutrient supply, especially for iron and zinc. In particular, the gains in iron in Southeast Asia and West Africa, and gains in zinc in South and Southeast Asia could contribute to reducing currently high incidences of micronutrient deficiencies (supplementary figure 2). We also expect that these combined dietary shifts will lead to substantial reductions in blue water demand and GHG emissions—potentially alleviating scarcity in countries where water is relatively scarce and contributing towards emissions reduction targets. Further, shifts towards both greater whole grains and increased shares of C4 cereals will be able to overcome the effects of reduced nutrient content under elevated CO₂ in many countries, though the outcomes are more muted for certain nutrients in Sub-Saharan Africa, South Asia, and the Middle East (figure 3). In general, our results show that a combination of locally feasible dietary shifts would likely produce strong co-benefits between increased nutrient supply and reduced environmental impacts with mixed outcomes for offsetting the effects of eCO₂.

4. Discussion

Global food systems face profound challenges in producing co-benefits for nutrition and the environment in the face of a changing climate. Because cereals play a central role in production and diets globally [1], their consideration will be essential in the development of solutions to achieve more sustainable food systems [29]. To this end, our study provides new insight into the potential contributions of cereals to achieve a more sustainable diet while incorporating country-specific preferences and acceptability. Specifically, we show that increasing the supply of whole grains can substantially enhance dietary nutrient supply and ameliorate the nutritional effects of eCO₂ and that maximizing C4 crops can lead to large reductions in environmental footprints (figure 2). More broadly, we demonstrate that a combination of complementary strategies can achieve co-benefits across multiple outcomes relevant to food system sustainability while also taking into consideration local preferences.

The acceptability of dietary shifts is a key consideration in our analysis. Because diets are shaped by



a variety of factors including local history, culture, food prices, and government policy [30, 31], they can be resistant to change towards sustainable choices [32]. By performing shifts based on observed shares of C4 cereals in diets and on realistic increases in whole grains, these scenarios represent transitions that are more readily achievable within specific contexts. However, we note that this cultural memory of historical dietary compositions depends in part on how far in the past such diets were consumed (see supplementary table 1). Such considerations should be incorporated into future work seeking to identify culturally appropriate sustainable diets beyond the cereal food group. All of the crops considered within each country have been (and still are) cultivated and consumed locally, thereby ensuring the presence of local knowledge regarding effective crop management and food preparation techniques. Dependent on this locally determined capacity for changes in dietary cereal supply, our analysis also highlights the extent to which outcomes may differ between countries. We find that some countries could realize large gains in dietary nutrient supplies (e.g. Nigeria, Mali, Indonesia), others could achieve reductions in their environmental burden (e.g. China, India, Yemen), while still others could experience multiple benefits (e.g. Central African Republic, Benin, Israel). As such, whether

the dietary shifts investigated here may ultimately be adopted by countries would be determined by both the specific benefits that the shifts may achieve (taking into account the wide variations in diets within a country) and the sustainability priorities of the country. Further, in cases where benefits may be relatively modest, solutions related to other food groups may offer greater promise for improving sustainability—an aspect which requires further investigation.

While the dietary changes investigated here provide strong evidence for the opportunities to improve human and environmental health, actualizing these shifts presents its own challenges, both from production and consumption perspectives. While agricultural research and development will be necessary to ensure that the yields of traditional crops (e.g. millets, sorghum) are universally comparable to those of more commercial cereals (e.g. rice, wheat, maize), there is already promising progress in this regard in many regions of the world. In Eastern and Southern Africa for instance, sorghum production doubled between 1980 and 2016 [33]. In India, the yields of sorghum and millet have increased between 1.9 and 2.9 times since the 1960s [1], and many districts already have sorghum and millet yields comparable to those of rice and maize [34, 35]. More generally, the provision of incentives that encourage transitions

in the production of these crops to more productive croplands—as opposed to more marginal fields where they are often cultivated [36]—will serve to further improve yields. Similarly, the shifts towards larger shares of whole grains that we consider are potentially feasible to achieve and are presently occurring in some places. Indeed, some countries and regions (e.g. India, the Middle East) already have the majority of their cereal supply met by whole grains [14]. In addition, as the category of ‘whole grains’ becomes better defined [37], this may allow for the inclusion of a greater variety of cereal-derived food items that offer the benefits of whole grains while allowing consumers greater flexibility in following dietary recommendations.

Realizing dietary shifts also depends on a host of factors including a person’s income, physical and social access, personal preferences, and willingness to change. Yet despite these potential obstacles, there is evidence to suggest that efforts to promote certain dietary choices can realize their desired outcomes. In certain cases, national and regional public awareness campaigns have proved to be effective [38]. For instance, campaigns on the health effects of high red meat consumption in the US and Europe have contributed to gradual reductions in consumption since the 1970s [39]. Market-based measures have also been employed as a potential mechanism for influence dietary choices. In India for instance, highly subsidized market prices for rice and wheat are partially responsible for the increased consumption of these cereals [40]. Other work has shown that subsidies on healthier substitutes can be effective in increasing the ratio of expenditure on healthy foods [41, 42]. In Singapore, the Health Promotion Board has intervened to make the price of cooking oils with lower saturated fat more competitive, leading to a replacement of roughly 30% of unhealthier oils in popular hawker stalls [43]. The inclusion of healthier food products in food assistance programs—such as the Supplemental Nutrition Assistance Program in the US [44] and the School Fruit Scheme in the EU [43]—has also led to modest increases in the consumption of healthier food substitutes and fruits and vegetables. All of this points to the potential for targeted interventions to promote shifts towards more sustainable yet locally acceptable cereal consumption baskets.

Achieving more sustainable diets requires the assessment of tradeoffs and co-benefits across multiple dimensions while accounting for country-specific preferences. Focusing on dietary cereal supply, our study has demonstrated the potential of two promising (and potentially complementary) dietary shifts to achieve multiple nutritional, environmental, and climate adaptation co-benefits. As countries seek to develop more sustainable food systems, our analysis provides a valuable approach for evaluating the multi-dimensional outcomes of potential demand-side solutions which can retain the benefits

of past dietary shifts while moving beyond their shortcomings.

Data availability statement

No new data were created or analyzed in this study.

Acknowledgments

We thank Ruth S DeFries, Samuel S Myers, and Matthew R Smith for their comments and suggestions on research design. We also thank Matthew R Smith for his assistance with the GENUS dataset.

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