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Country-specific dietary shifts to mitigate climate and water crises

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ABSTRACT

Undernutrition, obesity, climate change, and freshwater depletion share food and agricultural systems as an underlying driver. Efforts to more closely align dietary patterns with sustainability and health goals could be better informed with data covering the spectrum of countries characterized by over- and undernutrition. Here, we model the greenhouse gas (GHG) and water footprints of nine increasingly plant-forward diets, aligned with criteria for a healthy diet, specific to 140 countries. Results varied widely by country due to differences in: nutritional adjustments, baseline consumption patterns from which modeled diets were derived, import patterns, and the GHG- and water-intensities of foods by country of origin. Relative to exclusively plant-based (vegan) diets, diets comprised of plant foods with modest amounts of low-food chain animals (i.e., forage fish, bivalve mollusks, insects) had comparably small GHG and water footprints. In 95 percent of countries, diets that only included animal products for one meal per day were less GHG-intensive than lacto-ovo vegetarian diets (in which terrestrial and aquatic meats were eliminated entirely) in part due to the GHG-intensity of dairy foods. The relatively optimal choices among modeled diets otherwise varied across countries, in part due to contributions from deforestation (e.g., for feed production and grazing lands) and highly freshwater-intensive forms of aquaculture. Globally, modest plant-forward shifts (e.g., to low red meat diets) were offset by modeled increases in protein and caloric intake among undernourished populations, resulting in net increases in GHG and water footprints. These and other findings highlight the importance of trade, culture, and nutrition in diet footprint analyses. The country-specific results presented here could provide nutritionally-viable pathways for high-meat consuming countries as well as transitioning countries that might otherwise adopt the Western dietary pattern.

1. Introduction

Undernutrition, obesity, and climate change have been described as a synergy of pandemics (Swinburn et al., 2019). Together with freshwater depletion and other related ecological harms, these intersecting global challenges share food and agricultural systems as an underlying driver. Leveraging those patterns presents an opportunity to address multiple challenges in tandem, with an eye toward avoiding the unintended consequences of making progress in some areas at the expense of others. For many low- and middle-income countries, for example, messaging about sustainable diets is complicated by a persistent high prevalence of all forms of undernutrition (Development Initiatives, 2018). Accounting for these and other factors at a country-specific level could help inform efforts among high-meat consuming countries to better align diets with public health and ecological goals, while providing nutritionally-viable strategies for transitioning countries that

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might otherwise adopt the Western dietary pattern, particularly among their urban population.

Shifts toward plant-forward diets are essential for meeting climate change mitigation targets (Bajzelj et al., 2014; Bryngelsson et al., 2016; Hedenus et al., 2014) and remaining within planetary boundaries (Willett et al., 2019). These and other concerns have fueled efforts—proposed and enacted—to reduce animal product consumption through approaches including behavior change campaigns (de Boer et al., 2014d; Morris et al., 2014), environmental impact labeling (Leach et al., 2016), dietary recommendations (Fischer and Garnett, 2016), and taxes (Säll and Gren, 2015; Springmann et al., 2017; Wirsenius et al., 2011). At the same time, animals raised for food can provide a range of agro-economic benefits, including converting inedible crop residues and by-products into human-edible food, and utilizing the share of grassland unsuitable for crop production (Mottet et al., 2017). Furthermore, animal-source foods are a valuable source of protein and bioavailable micronutrients, especially for young children (de Pee and Bloem, 2009d; Semba, 2016; Swinburn et al., 2019).

Policy and behavioral interventions aimed at promoting sustainable diets could be better informed with evidence about where they could offer the greatest potential benefits, the nutritional status of different populations, and the relative environmental impacts of each diet in each country. Previous studies documenting ecological impacts of dietary scenarios have called for greater geographic specificity (Aleksandrowicz et al., 2016; Jones et al., 2016), as most have examined only one or a few—almost exclusively industrialized—countries, or a regional or global aggregate (Appendix A, Table A1).

To help address these gaps, we modeled the greenhouse gas (GHG) footprint and blue and green water footprint (WF) of baseline consumption patterns and nine increasingly plant-forward diets with varying levels of animal products for 140 individual countries and territories (henceforth: "countries"). Diets were modeled in accordance with health criteria, offering nutritionally-viable scenarios (to the extent possible without accounting for micronutrients) that adjust for over- and under-consumption. We account for blue water (surface and groundwater, e.g., for irrigation) and green water (soil moisture from precipitation); the latter is often excluded from similar studies on the rationale that it does not directly impact water scarcity (e.g., by depleting aquifers). Green water accounting is important, however, because efficient use of green water in rainfed agriculture can lessen reliance on blue water elsewhere. In an internationally-traded economy, one cannot be considered independently of the other, and both are part of an increasingly scarce global pool (Hoekstra, 2016; Schyns et al., 2019). We also incorporate footprints of aquatic animals, nuts, and seeds—common protein alternatives to terrestrial animal products—which most prior studies excluded or only narrowly considered (Appendix A, Table A1).

By accounting for import patterns and associated differences in the GHG and water footprints of food items based on the production practices unique to items' countries of origin (COO), the study model satisfies recent appeals (Heller and Keoleian, 2015; Wellesley et al., 2015) to incorporate trade flows when measuring the environmental impacts associated with national consumption patterns. Moreover, international accounting systems commonly attribute environmental impacts associated with imported foods to producing countries rather than the countries in which they are consumed, thereby displacing accountability away from the populations responsible for changing demand (Dario et al., 2014; de Ruiter et al., 2016; Peters and Hertwich, 2008).

This research identifies a range of country-specific scenarios in which dietary patterns could better align with climate change mitigation, freshwater conservation, and nutrition guidelines.

2. Methods

We developed a model to estimate the annual per capita and whole country GHG, blue water, and green water footprints for baseline consumption patterns and nine increasingly plant-forward diets specific to 140 countries. We also estimate the per-serving, per-kilocalorie, per-gram of protein, and per-kilogram edible weight footprints of common food groups. The model was developed in Python version 3.6. Model input and output are available in Mendeley Data (Kim et al., 2019).

2.1. Baseline consumption patterns

To characterize baseline consumption patterns for each country, we averaged data over the 2011–2013 Food and Agriculture Organization of the United Nations (FAO) food balance sheets (FBS) (FAO, 2017a), which provide estimates of per capita domestic food supplies after accounting for imports, exports, losses (where data are available), animal feed, and other non-food uses (FAO, 2001). Quantities reported in FBS reflect food availability and thus overestimate quantities actually consumed. Bovine meat supplies, for example, are reported in dressed carcass weight, which includes bones and other parts typically considered inedible. These data are appropriate for diet footprint modeling, however, because they reflect the amount of production involved in feeding populations (e.g., we measure the footprint of the carcass required to produce the edible portion of beef in the diet). Food balance sheets are also well-suited for comparing consumption patterns across countries (Fehrenbach et al., 2016) and have precedent in the literature for measuring diet footprints across regions (Hedenus et al., 2014; Popp et al., 2010; Pradhan et al., 2013; Tukker et al., 2011) and globally (Bajzelj et al., 2014; Stehfest et al., 2009; Tilman and Clark, 2014).

2.2. Food losses and waste

For some items in some countries, where sufficient data were available, FBS subtracted supply chain losses from food supply estimates. We added these quantities back in to food supplies for two reasons: First, estimates of diet footprints should reflect the fact that some amount of waste inevitably occurs between the producer and the consumer, thus for footprint modeling purposes we needed the original quantities of FBS items prior to supply chain losses. Second, in cases where it was appropriate to subtract supply chain losses—i.e., when dealing with amounts of calories or nutrients actually consumed (Section 2.4)—we used a more comprehensive source for food losses and waste (Gustavsson et al., 2011); combining this with FBS estimates would have resulted in double-counting. Detailed methods for estimating food losses and waste are provided in Appendix B.1.

2.3. Food items

Study diets were comprised of 74 items in FBS (Mendeley Data input/item_parameters). Twenty-four additional FBS items were excluded due to the small quantities in which they are typically consumed (e.g., spices), limited footprint data (e.g., game meats), and/or because they are not typically considered food (e.g., alcohols, cottonseed). Most FBS items are expressed in terms of primary equivalents, i.e., the quantity of a raw commodity required to produce a given quantity of processed goods. For example, wheat products (e.g., wheat flour and bread) are quantified in terms of the unprocessed wheat required for their production, and dairy products, except for butter and cream, are quantified as whole milk equivalents (FAO, 2001; 2017b). FBS items range from specific (e.g., bananas) to broad (e.g., freshwater fish). Other model inputs, including trade data and item footprints, were expressed in terms of specific items (e.g., walnuts), so we developed schemas to match them to the associated FBS items (e.g., nuts and products).

For modeling purposes, we added several custom items to represent foods either not included in FBS (e.g., edible insects) or more specific than those in FBS. The custom item for forage fish, for example, includes small, schooling pelagic fish such as sardines and herring that

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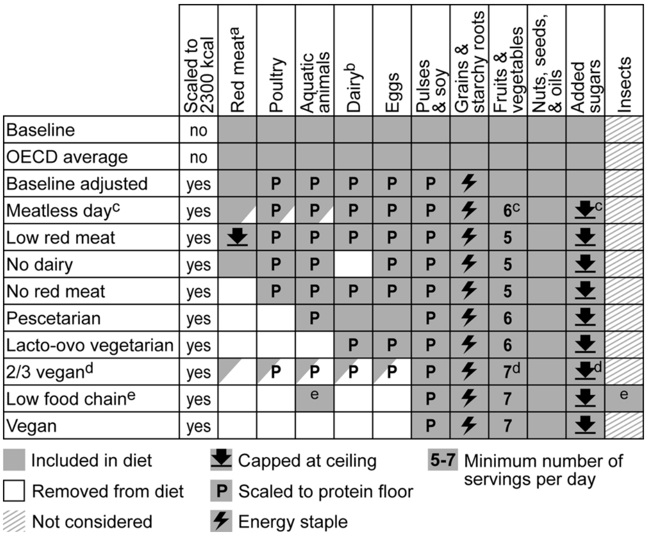

Fig. 1. Parameters for study diets. Partial shading indicates food groups that were included only on selected days/meals, e.g., meat was included in six of seven days for meatless day, and in one of three meals for two-thirds vegan.
[a]Red meat includes bovine, sheep, goat, and pig meat.
[b]When dairy products were scaled to meet the protein floor, only the FBS item "Milk, Excluding Butter" (which also includes some milk-derived products such as cheese and yogurt) was scaled. The FBS items "Butter, Ghee" and "Cream" were not scaled for protein.
[c]The fruits and vegetables floor and added sugars cap for meatless day were only applied for one day of the week, reflecting one day of the lacto-ovo vegetarian diet and six days of the adjusted baseline.
[d]The 2/3 vegan diet reflects the vegan diet for two out of three meals per day and the adjusted baseline for the third. The fruits and vegetables floor and added sugars cap were only applied to the two vegan meals.
[e]For the low-food chain diet, protein from insects replaced 10% of the protein from terrestrial animal products, and protein from forage fish and bivalve mollusks replaced 70% and 30%, respectively, of the protein from aquatic animals.

are prey for larger species, and unlike the FBS item "Pelagic Fish" it does not include larger species such as tuna. In Mendeley Data, custom items are identifiable by an FBS item code of 9000 or greater.

2.4. Modeled diets

For each of the 140 study countries, we modeled nine increasingly plant-forward diets that adhered to parameters for a healthy diet (summarized in Fig. 1; see also Mendeley Data input/item_parameters). Each diet used the country's baseline consumption pattern as the starting point. In all steps where groups of FBS items (e.g., protein foods) were scaled up or down, the relative proportions of items within each group were preserved, reflecting each country's unique dietary pattern. For example, the residents of South Korea consume relatively little dairy, so if they removed red meat from their diet we would not expect milk products to be a popular protein substitute. When comparing FBS item quantities with nutritional criteria (e.g., the target for caloric intake described below), we first subtracted region- and food group-specific losses occurring during processing and packaging, distribution, and consumption (Gustavsson et al., 2011). This step ensures that criteria are met based on quantities that are closer to amounts actually consumed, versus quantities in the food supply.

Diets were modeled as follows. First, to adjust for over- and under-consumption, the baseline pattern was scaled to 2300 kilocalories—the upper bound of average per capita energy requirements calculated by Springmann et al. (2016). We held caloric intake constant across all modeled diets for consistency when making cross-country comparisons. In the steps described below (e.g., removing animal foods), the caloric content of the diet underwent further changes and subsequently had to be adjusted back to 2300, but performing this step first kept the relative proportions of FBS items closer to the baseline. Following the initial adjustment for caloric intake, amounts of nuts, seeds, and oils were held constant for all diets.

Where applicable, selected animal foods were removed (Fig. 1); e.g., terrestrial and aquatic meats were removed from the lacto-ovo vegetarian diet. Modeled diets were then adjusted to meet two health guidelines from the World Health Organization and FAO (2003): Fruits and vegetables (excluding starchy roots, e.g., potatoes, yams) were scaled up to a floor of 400 g per day, or approximately five servings; and added sugars were capped to contribute no more than 10% of total energy intake. For diets in which meat was eliminated, the fruit and vegetable floor was raised to six or seven servings per day (Fig. 1), based on the rationale that healthy vegetarian and vegan dietary patterns tend to include more of these items (Springmann et al., 2016). Note that we use the term "vegan" to refer to exclusively plant-based diets, without reference to other behaviors sometimes associated with the term, such as avoidance of leather products.

The low red meat diet additionally included a cap on red meat (i.e., bovine, sheep, goat, pig) of 350 g cooked weight per week, or roughly three servings, as per recommendations (World Cancer Research Fund and American Institute for Cancer Research, 2018). We converted the 350 g cap from cooked to raw weight (467 g) using the same conversion factors we used for per-serving footprints (Section 2.8, Mendeley Data input/per_unit_serving_sizes), and from raw weight to carcass weight (648 g) using the average of FAO extraction rates for bovine and pig meat (FAO, 2017). Taken together with adjustments for added sugars, fruits and vegetables, calories, and protein, this diet is intended to approximate the adoption of dietary recommendations.

For the low food chain diet, protein from insects replaced 10% of the protein from terrestrial animal products, and protein from forage fish and bivalve mollusks replaced 70% and 30%, respectively, of the protein from aquatic animals. Insects are not included in FBS, so nutritional content was derived from Payne et al. (2016). Forage fish and bivalve mollusks are included in FBS but grouped with other items (e.g., "Molluscs, Other" includes snails), so nutrient content was derived from the United States Department of Agriculture (USDA) food composition database (USDA, 2017). See Mendeley Data input/nutrient_comp_custom_items for details.

Following these adjustments, selected energy staples, i.e., FBS items in the grains and starchy roots groups, were scaled up or down to return to the 2300 kilocalorie target. Selected protein groups (Fig. 1) were then scaled up as needed to meet a protein floor of 69 g per day—12% of total energy intake, within the recommended range of 10–15% (World Health Organization and FAO, 2003). To hold calories constant while scaling up protein, caloric increases from protein foods were counter-balanced with commensurate reductions in calories from energy staples. The equation for this step is provided in Appendix B.2.

We also modeled an adjusted variant of the baseline pattern, scaled to 2300 kcal and the protein floor (Figs. 1, 5b, 6). When comparing plant-forward modeled diets with baseline consumption patterns, the adjusted baseline allows for isolating the effects of food substitutions independent of adjustments for over- and under-consumption.

The meatless day and two-thirds vegan diets were modeled as combinations of two diets. Meatless day was patterned after behavior change campaigns promoting one day of the week without meat (e.g., Meatless Monday) and assumes a lacto-ovo vegetarian diet for one day per week and the adjusted baseline for the other six days. We included this diet because it can serve as an entry point toward more plant-forward diets. Two-thirds vegan was patterned loosely after "Vegan Before 6" (Bittman, 2013) and assumes a vegan diet for two out of three meals per day and the adjusted baseline for the third, with each meal providing equal caloric content. This approach does not account for the possibility that people in some countries may consume more animal products at dinner, for example, compared to breakfast and lunch.

We also included a hypothetical scenario in which all study countries adopt the average baseline consumption pattern of high-income OECD countries (The World Bank, 2018; Figs. 1, 6 and 8a–d), illustrating potential outcomes of the Western diet becoming more widespread. Furthermore, by holding diet composition constant across countries, this scenario isolates the effects of import patterns and COOs on GHG and water footprints.

2.5. Countries

We ran the model for the 140 countries with sufficiently robust trade and food supply data for inclusion in the 2011–2013 FAO detailed trade matrices and FBS (FAO, 2017a).

2.6. Import patterns and countries of origin

An item's footprint varies based on the conditions and practices specific to its COOs (e.g., Figs. 3 and 4). To account for these differences, for each country and diet, we traced the supply of each FBS item back to the countries in which it was produced. Of Japan's pig meat supply, for example, 48% was produced domestically over 2011–2013, 22% was imported from the United States (US), 10% from Canada, 7% from Denmark, and so on. For total imports by importing country and FBS item, we used trade data averaged over 2011–2013 FBS, and to allocate the share of total imports among COOs, we used 2011–2013 FAO detailed trade matrices (FAO, 2017a). Detailed methods are provided in Appendix B.3. Note that for this study, COOs were only relevant in cases where sufficient country-specific item footprint data were available.

2.7. Diet footprints

2.7.1. Overview

Contributions of FBS items to diet footprints were modeled using two approaches. The first method used country-specific footprints, i.e., for the items consumed in a given country, the GHG and water footprints were specific to the COOs from which each item was imported. Since we did not have sufficient country-specific data to apply this method in all cases, it was limited to the GHG and water footprints of terrestrial animal products (excluding insects), WFs of plant foods, and all land use change (LUC) CO_2 footprints. After adapting country-specific footprint data to FBS items, this method yielded 16 009 footprint data points (available in Mendeley Data input/item_footprints_by_coo). These were then multiplied by the corresponding quantities of each item, allocated over COOs, in each country-diet combination. This method and the associated data sources are described in Sections 2.7.2–2.7.4 with technical details covered in Appendix B.4.

The second method was used in cases where we did not have sufficient country-specific data to differentiate footprints by COO, i.e., for the GHG and water footprints of aquatic animals and insects, and the GHG footprints of plant foods. For this method we performed a literature search and adapted results from 114 peer-reviewed studies, yielding 764 data points (available in Mendeley Data input/item_footprints_distributions). For these item-footprint pairs, we used a bootstrapping approach to reflect the heterogeneity across the countries and production systems examined in the 114 studies. The bootstrapping approach is described in Sections 2.7.5–2.7.6, with the literature search described in Appendix B.5.

All results reflect cradle-to-farm gate activities only, and thus do not account for GHG and water footprints associated with processing, transportation, retail and preparation. This limitation is discussed in Section 3.3.

While most FBS items are expressed in terms of primary equivalents, there were some cases where we needed to allocate shares of GHG and water footprints among processed items originating from the same root product, e.g., butter and cream from milk. We adapted the economic allocation method described in Hoekstra et al. (2011). The method and how it was applied in each case are described in Appendix B.6.

2.7.2. GHG and land-use change CO_2 footprints of terrestrial animal products, by COO

For GHG footprints of terrestrial animal products (excluding insects), we adapted data from FAO's Global Livestock Environmental Assessment Model GLEAM-i tool (FAO, 2017c). The tool applies a consistent, transparent approach to quantifying production data and GHG emissions associated with terrestrial animal production specific to 235 different countries, accounting for differences in feed composition, feed conversion ratios, manure management techniques, and other parameters associated with the various species and production systems (e.g., grasslands cattle, feedlot cattle, broiler chickens, layer chickens) unique to each setting. The level of granularity provided by GLEAM-i further allowed us to report CO_2 emissions from deforestation-driven LUC separately from other emissions sources. These qualities made GLEAM-i a robust choice for differentiating GHG footprints based on COO.

Although GLEAM-i accounts for soil carbon fluxes associated with land use change, e.g., conversion from forest to grassland, it does not account for the effects of livestock management practices on soil carbon losses or sequestration—an important limitation that should be addressed in future research (see Section 3.3). Furthermore, GLEAM-i does not allocate GHG emissions to offals and other slaughter byproducts, thus overestimating the GHG footprints of meat and underestimating those of offals (see Appendix B.6).

With the exception of offals, the GLEAM-i tool allocates GHG emissions from each production system among the associated animal products (e.g., cattle meat and milk from grassland systems in Brazil) based on protein content. The GHG footprints of these items, as reported by GLEAM-i, are specific to country, production system, and item but are not specific to the emissions source (i.e., LUC for soy feed, LUC for palm kernel cake feed, LUC for pasture expansion, and all other sources of GHG emissions). One of our study aims was to highlight the contributions of deforestation to GHG footprints. To this end, we allocated the GHG footprints of items among emissions sources based on the assumption that within a given a country and production system, the relative shares of *source-specific* GHG emissions among the items from that system is the same as the relative shares of *total* GHG emissions among those items, which was provided by GLEAM-i. For example, for United Kingdom (UK) layer systems, based on GLEAM-i data, 82% of the total GHG footprint was allocated to eggs and 18% was allocated to poultry meat. Thus, we applied the same percentages to allocate LUC CO_2 emissions from the use of soy feed in UK layer systems (also reported by GLEAM-i) between eggs and meat. The equations for this method are detailed in Appendix B.4.

Since GLEAM-i reports GHG footprints per kilogram of protein, we converted to per-kilogram primary weight footprints (e.g., carcass weight for meat, whole milk for dairy) as follows. For each GLEAM-i item g produced in country c, the primary weight GHG footprint GHG was calculated as

$$GHG_{c,g} = GHGP_{c,g} \times \frac{PP_{c,g}}{P_{c,g}}$$

where $GHGP$ is the GHG footprint per kilogram of protein, PP is the annual production in kilograms of protein, and P is the annual production in kilograms primary weight.

Footprints of GLEAM-i items (e.g., buffalo meat, cattle meat) then needed to be translated to footprints of FBS items (e.g., bovine meat). We developed schemas matching GLEAM-i countries and items to those used in FBS. For each FBS item f produced in country c, we then calculated the primary weight GHG footprint as the average footprint of the associated GLEAM-i item(s) g produced in c, weighted by the tonnages produced P:

$$GHG_{c,f} = \frac{\sum_{g\ \mathrm{in}\ c} (GHG_{c,g} \times P_{c,g})}{\sum_{g\ \mathrm{in}\ c} P_{c,g}}$$

If there were no GLEAM-i footprint data for an FBS item in a given country, we used a regional average, weighted by the tonnage of the FBS item produced in each country (FAO, 2017a), as follows:

$$GHG_{r,f} = \frac{\sum_{c \in r} (GHG_{c,f} \times P_{c,f})}{\sum_{c \in r} P_{c,f}}$$

Finally, if there were no footprint data for *f* in *r,* a weighted global average was used.

2.7.3. Land-use change CO_2 footprints of soy and palm oils intended for human consumption, by COO

Soybeans, soybean oil, palm oil, and palm kernel oil reported in FBS food supply data reflect uses for human consumption; GHG footprints of soy and palm as animal feed are described in Section 2.7.2. Land-use change CO_2 footprints for the former items were adapted from FAO GLEAM documentation (FAO, 2017d), which provides per-hectare LUC CO_2 footprints associated with soy and palm production for 92 (soy) and 14 (palm) countries. Per-hectare footprints were converted to per-kilogram footprints using country-specific crop yields from FAOSTAT, averaged over 2011–2013. The LUC CO_2 footprints of soy and palm oils were then derived from their root products using the economic allocation method described in Appendix B.6. If there were no LUC CO_2 footprint data associated with soy or palm production in a given country, the LUC CO_2 footprint was assumed to be zero.

2.7.4. Water footprints of plant foods and terrestrial animal products, by COO

We adapted data from literature quantifying the blue and green WFs of plant foods (Mekonnen and Hoekstra, 2010a) and terrestrial animal products (Mekonnen and Hoekstra, 2010b) specific to over 200 countries. We developed schemas matching countries and items from these datasets to their FBS counterparts. Parallel to our approach for GHG footprints, for each FBS item *f* produced in country *c,* we calculated the WFs as the average footprint of the associated water dataset item(s) *w* produced in *c*, weighted by the tonnages produced *P* (FAO, 2017a):

$$WF_{c,f} = \frac{\sum_{w\ \mathrm{in}\ c} (WF_{c,w} \times P_{c,w})}{\sum_{w\ \mathrm{in}\ c} P_{c,w}}$$

If there were no country production data for an item *w*, an unweighted country average was used. If there were no WF data matching FBS item *f* produced in country *c*, a weighted regional or global average footprint was used, following the method described above for GLEAM-i.

One FBS item (honey) had no associated WF data and was thus excluded from WF calculations. Mekonnen and Hoekstra's datasets did not include insects, so the WF of insects was taken from Miglietta et al. (2015) and used for insect production in all countries.

Note that this method does not account for levels of water scarcity in countries of origin. While we acknowledge that there are differing perspectives regarding the need for scarcity-weighted WFs, our approach is informed by Hoekstra (2016), which argues that WFs have implications for freshwater conservation wherever withdrawal occurs. In an internationally-traded economy, all freshwater is part of an increasingly scarce global pool. Even in regions with abundant freshwater availability, if water is used inefficiently in agriculture or aquaculture, wasted water is water that could have otherwise been used to produce more food—thus lessening the need for other, potentially water-scarce, regions to produce as much.

2.7.5. Bootstrapping approach for GHG footprints of plant foods, aquatic animals, and insects

In contrast to the datasets used for footprints by COO—which used uniform methods across FBS items and countries—plant food, aquatic animal, and insect GHG footprints from the literature search reflected a diversity of studies with varied methods, and represented some countries more than others. To maximize consistency across studies and with the country-specific data describe above, we applied strict inclusion/exclusion criteria and standardized results to the degree possible (described in Appendix B.5); however, the practices under study still varied greatly, e.g., by fertilizer and pesticide application rates, use of organic practices, irrigation method, crop rotations, use of protected cultivation (e.g., greenhouses), fish stocking density, and fishing method (e.g., long-lining, trawling). These may not be representative of the prevailing practices for a given country-item combination.

To account for this heterogeneity, we create a weighted probability distribution for each FBS item's footprint observations. When a study provided results for multiple scenarios involving the production of the same item in the same country, e.g., for five GHG footprint observations for Spanish wheat with varying levels of nitrogen fertilizer inputs, we assigned a weight to each observation equal to the reciprocal of the number of observations, e.g., 1/5, preventing studies with multiple observations from being overrepresented. If there were no observations for an FBS item, proxies were used, e.g., a distribution of all grains footprints was used for sorghum and products, and a distribution of all citrus fruit footprints was used for grapefruit and products. All item footprint distributions used in the model are provided in Mendeley Data input/item_footprints_distributions.

To calculate the contributions of plant foods, aquatic animals, and insects to the GHG footprint of a country-diet combination, we used a bootstrapping approach designed to capture the distribution of item footprint values from the literature. The weighted distribution of GHG footprint values for tomatoes, for example, was skewed right; simply using the median or average would ignore this important detail. For our approach, we 1) selected 10 000 random samples from each FBS item footprint distribution, e.g., 10 000 samples from 23 weighted GHG footprint values (kg CO_2e/kg) for barley; 2) multiplied each sampled footprint value by the corresponding quantity of the FBS item in the diet, e.g., 46 kg barley/capita/year in the Moroccan vegetarian diet; and 3) summed the resulting values for FBS items within the same group, e.g., resulting in a distribution of 10 000 values for the kg CO_2e/capita/year associated with grains in the Moroccan vegetarian diet. Summing the median value from each distribution with results by COO (Sections 2.7.2–2.7.4) yielded the total per capita footprint of a given country diet. We also present interquartile ranges (error bars in Fig. 7, also provided in Mendeley Data output) to convey variations across bootstrapped outputs. Note that these ranges apply only to items for which bootstrapping was used, as the COO-specific method does not account for uncertainty and is deterministic, returning a single footprint value for each permutation of inputs (e.g., FBS item, diet, country, and COO).

2.7.6. Bootstrapping approach for water footprints of aquatic animals

Aquatic animal WFs were limited to farmed species and accounted for blue and green WFs associated with feed production and, where applicable, blue water used to replace evaporative losses from freshwater ponds and to dilute seawater in brackish production. Water footprints of wild-caught aquatic animals were assumed to be negligible.

For feed-associated WFs, we created a distribution of WF values adapted from Pahlow et al. (2015) for each FBS item associated with farmed species. We did not have information about the share consumed in a given country that was farmed versus wild-caught, so we made assumptions based on 2014 global production patterns, e.g., 79% of harvests associated with the FBS item "Freshwater Fish" were from aquaculture (FAO, 2017e), so when this item was included in diets, we only applied the feed-associated WF to 79% of the amount consumed regardless of the country.

For freshwater pond aquaculture, we created a distribution of blue WF values for each of the FBS items "Freshwater Fish" and

"Crustaceans" (Gephart et al., 2017; Henriksson et al., 2017; Verdegem and Bosma, 2009). For "Crustaceans" we created an additional distribution of blue WF values for brackish water pond aquaculture (Henriksson et al., 2017; Verdegem and Bosma, 2009). Both distributions were weighted using the method described in Section 2.7.5, except for the 31 values for freshwater production in China from Gephart et al. (2017), which were weighted by the percentage of Chinese freshwater production represented by each data point. We did not have information about the shares consumed in a given country that were from freshwater or brackish ponds, so as per our method for feed-associated WFs, we made assumptions based on 2014 global production patterns (FAO, 2017e; Mendeley Data input/aquaculture_percent_ponds).

Contributions of aquatic animals to country-diet WFs were calculated as follows, using the bootstrapping approach described in Section 2.7.5. We (1) selected 10 000 random samples from each FBS item-footprint distribution, e.g., for "Crustaceans" we selected 10 000 samples each from the distributions for feed blue WF, feed green WF, freshwater pond blue WF, and brackish water pond blue WF; (2) multiplied each sampled footprint value by the corresponding quantity of the FBS item in the diet; and (3) summed the resulting values for FBS items within the same group, i.e., "Aquatic animals," keeping results for each water footprint type separate.

2.8. Footprints of individual food items

In addition to calculating diet footprints, we presented per-serving, per-kilocalorie, per-gram of protein, and per-kilogram edible weight footprints associated with grouped FBS items (Figs. 2, S1–S3). For per-kilogram footprints, we converted carcass weight and whole aquatic animal footprints of terrestrial and aquatic meats to edible weight equivalents (FAO, 1989, n.d.; Nijdam et al., 2012; Waterman, 2001). Where nut footprints were expressed in terms of in-shell, we converted them to shelled. Although the model handled dairy products in terms of whole milk equivalents (except for butter and cream), for comparative purposes we added the footprints of cheese and yogurt, derived from milk using economic allocation (see Appendix B.6). Per-kilogram edible weight footprints were then converted to per-serving footprints using US standards (U.S. Food and Drug Administration, 2016). Serving sizes and conversion factors are provided in Mendeley Data input/per_unit_serving_sizes.

In addition to presenting the median and interquartile range for each group footprint, for groups with footprints specific to COO, we calculated global averages weighted by the mass produced in each country. For groups with footprints from our literature search, averages were weighted by the reciprocal of the number of observations from each study to prevent studies with multiple observations from being overrepresented (consistent with the weighting method described in Section 2.7.5).

3. Results and discussion

3.1. Footprints of individual food items

Our study model incorporated 3850 GHG, 5402 blue water, and 7521 green water data points (Mendeley Data input/item_footprints_by_coo, input/item_footprints_distributions) reflecting cradle-to-farm gate footprints of the individual food items comprising diets, spanning diverse production practices and conditions unique to COO. These are presented per serving (Fig. 2), per kilocalorie (Fig. S1), per gram of protein (Fig. S2) and per kilogram edible weight (Fig. S3) as global averages weighted by the tonnage produced in each country (where sufficient country-specific data were available). These figures show footprint values aggregated over common food groups (e.g., grains), whereas the study model handled items with greater specificity (e.g., maize, millet, barley).

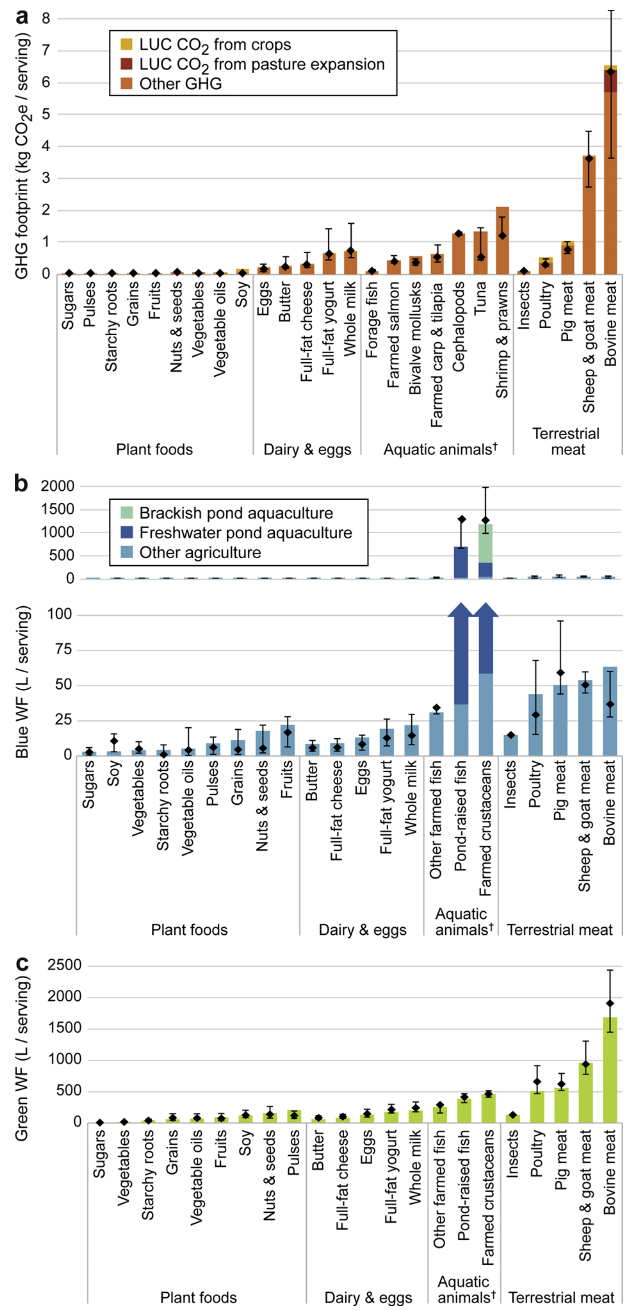

Fig. 2. Average per serving (a) GHG, (b) blue water, and (c) green water item footprints. For items with sufficient country-specific footprint data (i.e., GHG and water footprints of terrestrial animal products excluding insects, WFs of plant foods, and LUC CO_2 footprints), footprints were averaged across countries and weighted by the tonnage produced in each country. For all other items (i.e., from the literature search), see Section 2.7.5 for how averages were weighted. Most items shown here are grouped (e.g., grains); footprints associated with specific items used in the study model (e.g., maize, millet, barley) are provided in Mendeley Data input. Diamonds represent medians and error bars show interquartile ranges. See Mendeley Data input/per_unit_serving_sizes for primary weight to serving size conversions.

† Forage fish GHG footprints are based on sardines and herring. Pond-raised WFs largely reflect tilapia, carp and catfish. Blue WFs for brackish pond aquaculture reflect freshwater used to dilute seawater. Water footprints of wild-caught aquatic animals were assumed to be negligible.

Whether by serving, energy content, protein, or mass, ruminant meats (i.e., bovine, sheep, goat) were by far the most GHG-intensive items. Per serving, bovine meat (weighted average: 6.54 kg CO_2e/serving) was 316, 115, and 40 times more GHG-intensive than pulses, nuts and seeds, and soy, respectively. Insects (e.g., mealworms, crickets) and forage fish (e.g., sardines, herring) were among the more climate-friendly animal products, much more so than dairy. Plant foods were generally the least GHG-intensive overall, often by an order of magnitude, even after accounting for GHGs associated with deforestation for palm oils and soy.

Blue WFs of pond-raised fish (e.g., carp, tilapia, catfish; weighted average: 698 L/serving) and farmed crustaceans (e.g., shrimp, prawns, crayfish; weighted average: 1184 L/serving) exceeded those of other item groups by an order of magnitude. Our model accounted for water used in production ponds and crop production for aquaculture feed. Refilling ponds to replace evaporative losses, together with freshwater used to dilute seawater in brackish production, accounted for 94.7% and 95.1% of the blue WFs for pond-raised fish and farmed crustaceans, respectively.

Bovine meat was the only item group for which the weighted average blue WF was greater than the 75th percentile blue WF. This suggests that most bovine meat production occurs in countries where blue water use for bovine meat is particularly high.

The wide interquartile ranges of country-specific item footprints (error bars in Figs. 2, S1–S3; see also Figs. 3 and 4) illustrate variations in the conditions and practices unique to where items are produced. The per-kilogram GHG footprints of bovine meat from Paraguay and Brazil, for example, were 17 and five times higher, respectively, than that of Danish bovine meat (Fig. 3). These differences were largely attributable to deforestation for grazing lands and higher methane emissions from ruminant eructation (belching). While there were insufficient data to account for COO in all cases, we did so for most of the items with the greatest magnitude and variance in footprints, e.g., GHG footprints of terrestrial animal products (excluding insects).

3.2. Footprints of whole diets

We modeled scenarios illustrating the potential per capita and whole-country footprints of nine plant-forward diets. These in part reflect modeling choices; they represent potential outcomes for consideration and may not reflect actual consumption behaviors. Scenarios involving country-wide shifts to a particular diet, for example, are unlikely to occur, but can reveal opportunities where policy and behavioral interventions could have the broadest effect, particularly in populous countries (Figs. 6b, 8c and d).

3.2.1. Global implications of adopting the OECD diet

In a scenario in which all 140 study countries adopted the average consumption pattern of high-income OECD countries, per capita diet-

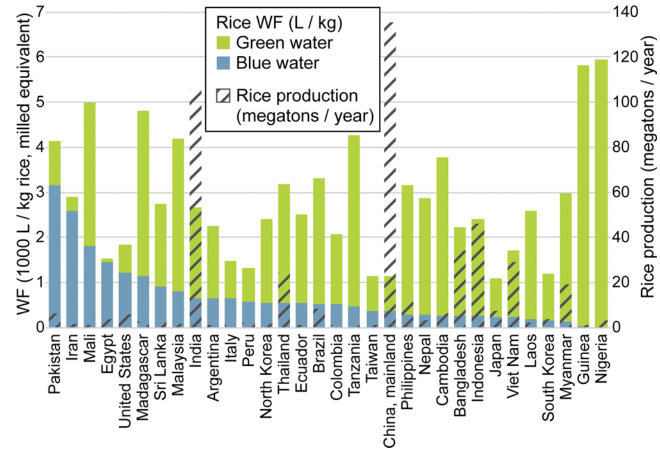

Fig. 4. Per-kilogram blue and green WFs of rice, by producing country, shown for countries that produced over 1 000 000 metric tons (1 megaton) in 2011–2013.

related GHG and consumptive (blue plus green) water footprints increased by an average of 135 and 47 percent, respectively, relative to the baseline (shown for selected countries in Figs. 6, 8a–d). These findings echo prior literature (e.g., Bajzelj et al., 2014; Willett et al., 2019) on the climate implications of rising meat and dairy intake, and the importance of both reducing animal-product intake in high-consuming countries and providing viable plant-forward strategies for transitioning countries.

3.2.2. Global implications of adjusting for under-consumption

We modeled scenarios in which dietary patterns could better align with ecological goals alongside nutrition guidelines—while also identifying some of the challenges in doing so. For example, baseline protein and caloric availability were below recommended levels (Section 2.4) in 49 and 36 percent of countries, respectively. The resulting adjustments for under-consumption attenuated—and in some cases completely offset—the GHG and water footprint reductions associated with dietary shifts. For a scenario in which all 140 study countries adopted either the low red meat or meatless day diet, our model projected an average net increase in diet-related GHG, blue water, and green water footprints relative to the baseline (Fig. 5a). Populous countries characterized by under-consumption were the largest contributors to this phenomenon, namely India and to a lesser degree Pakistan and Indonesia (Figs. 6–8); loss-adjusted baseline protein availability in these

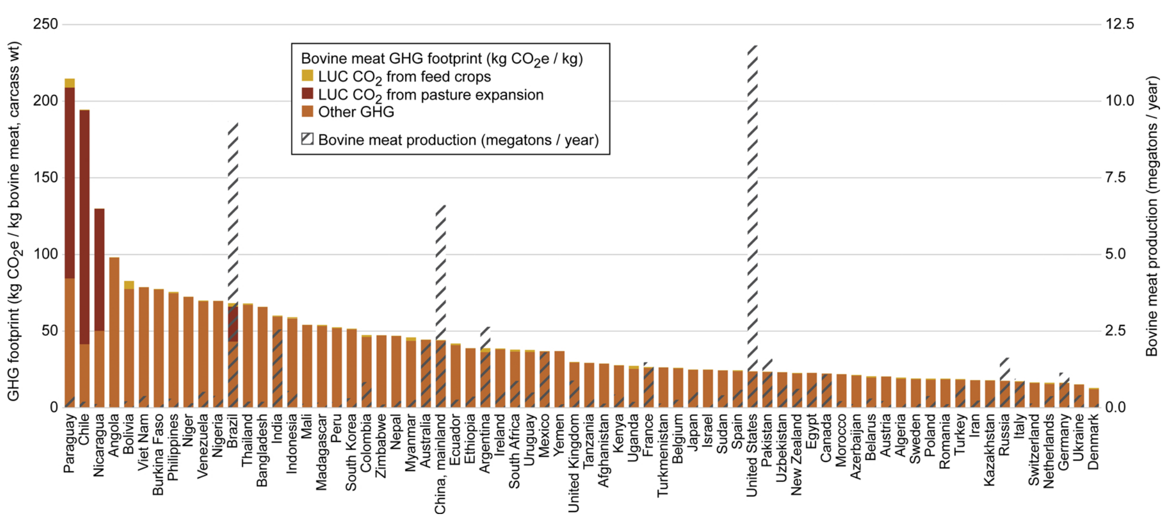

Fig. 3. Per-kilogram GHG footprints of bovine meat, by producing country, shown for countries that produced over 100 000 metric tons in 2011–2013.

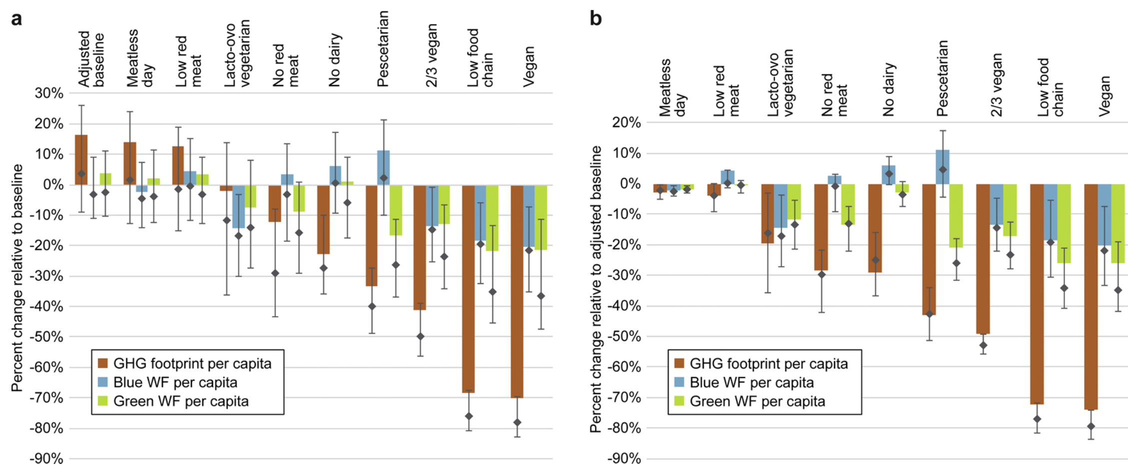

Fig. 5. Potential per capita changes in diet-related GHG, blue water, and green water footprints across all 140 study countries, calculated as the average Δfootprint weighted by the population of each country. Shown for the nine modeled diets relative to (a) baseline consumption patterns and (b) an adjusted variant of each country's baseline, scaled to 2300 kcal with a 69 g/capita/day protein floor. The adjusted baseline allows for comparisons between plant-forward diets and baseline patterns independent of adjustments for over- and under-consumption, isolating the effects of food substitutions. Diamonds represent medians and error bars show interquartile ranges.

countries was 14, 9, and 12 g below the recommended minimum of 69 g, respectively. Thus, interventions that aim to address both sustainability and health goals must ensure plant-forward shifts are ambitious enough to offset the potential ecological burdens associated with providing adequate nutrition.

By contrast, if we hold caloric intake constant—that is, independent of adjustments for over- and under-consumption (i.e., relative to an adjusted variant of the baseline pattern, scaled to 2300 kcal and the protein floor)—shifting to the low red meat or meatless day diets resulted in an average net 4% or 3% reduction in diet-related GHG footprints, respectively (Fig. 5b). Regardless of their effectiveness in climate change mitigation, these modest shifts may offer an accessible starting point toward more plant-forward dietary patterns.

3.2.3. Importance of country-specific analyses, trade, and countries of origin

The global aggregates shown in Fig. 5 are limited insofar as they obscure the considerable variation across countries, illustrated by the interquartile ranges. This variation was attributable to differences in food supply composition (e.g., the degree to which the aquatic animals group is comprised of pond-raised species), how animal products are replaced when shifting diets, adjustments for over- and under-consumption, and import patterns and the associated production practices (e.g., pasture-based vs. intensive; irrigated vs. rainfed) and climatic conditions (e.g., precipitation, evapotranspiration) unique to COOs. A country-specific analysis reveals, for example, that shifting to the meatless day diet reduced GHG and water footprints in 47% and 57% of study countries, respectively—with some of the greatest per capita reductions in Paraguay, Israel, and Brazil—even though the average net effect was an increase in footprints. Fig. 7 further illustrates the degree to which the relative environmental benefits among diets varied across countries, along with the relative contributions of different food groups. Notably, of the 140 individual countries examined in this study, most—including those identified as having the most GHG- and water-

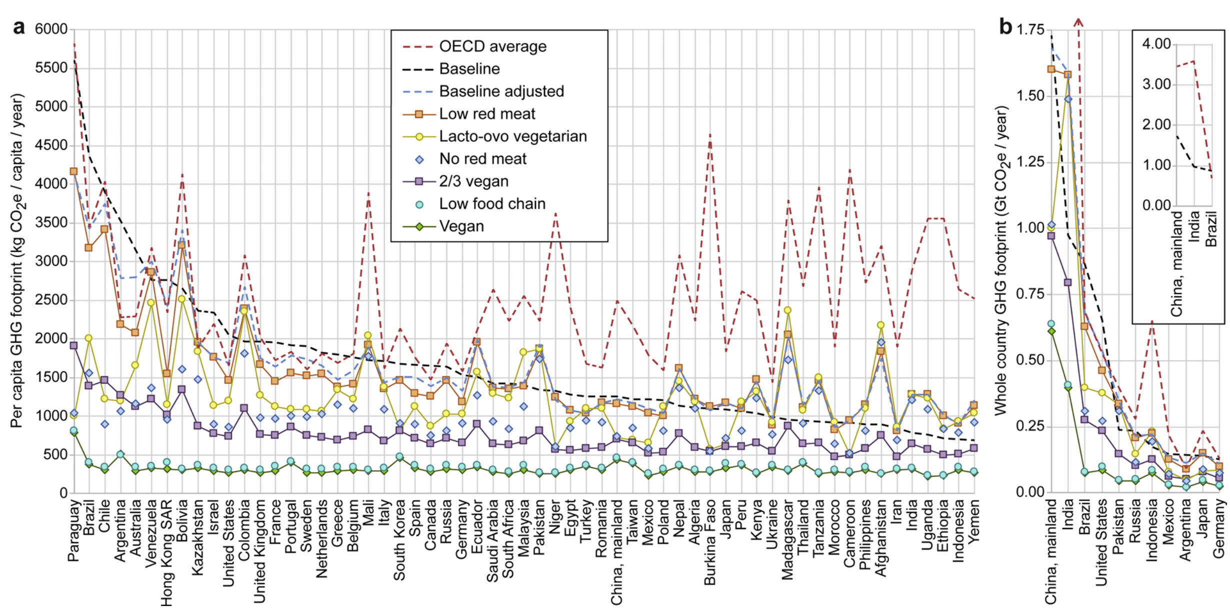

Fig. 6. Greenhouse gas footprints for selected diets, by country, (a) per capita and (b) for whole country populations. Countries are sorted by baseline footprint. Due to space constraints, of the 140 study countries, only the following are shown here: (a) the 59 countries above the 58th percentile for whole country baseline footprint, and (b) the 11 countries above the 92nd percentile for whole country baseline footprint.

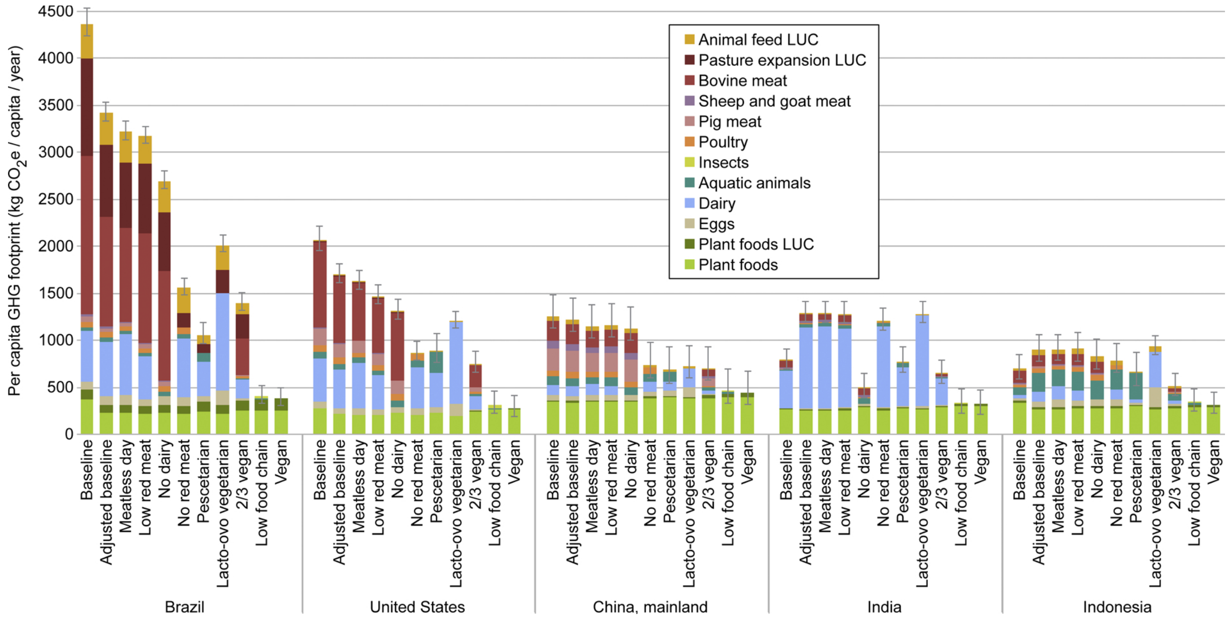

Fig. 7. Per capita diet-related GHG footprints by country, diet, and food group. Shown for the top four countries with the largest whole-country diet-related baseline GHG footprints: (1 st) mainland China, (2nd) India, (3rd) Brazil and (4th) the United States. Indonesia, ranked 7th for whole-country footprint, is also shown as an example of a country with high consumption of aquatic animals. Most items shown here are broadly grouped (e.g., plant foods); diet footprints are provided with greater specificity in Mendeley Data output. Error bars show interquartile ranges and apply only to items for which bootstrapping was used, i.e., plant foods, aquatic animals, and insects (see Section 2.7.5).

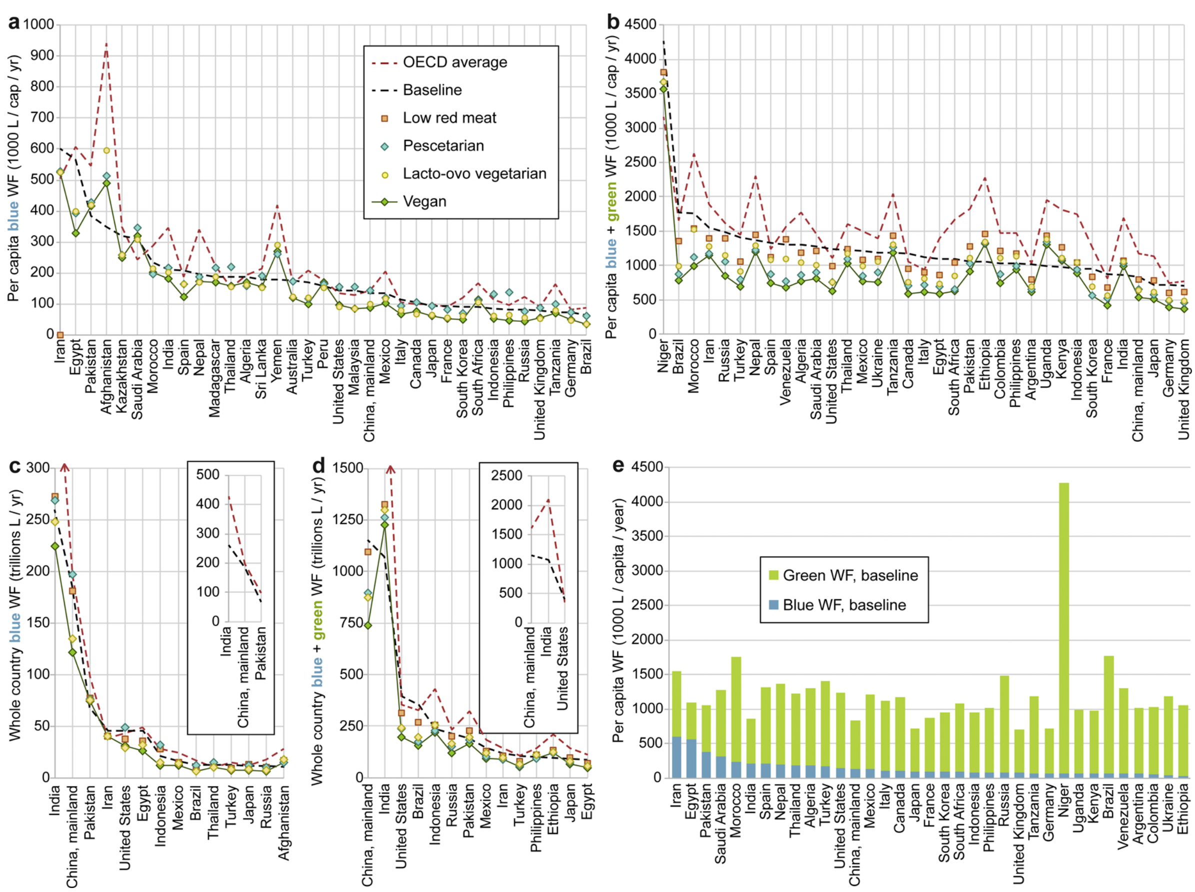

Fig. 8. Water footprints by country (a) per capita, blue WF only; (b) per capita, combined blue plus green WFs; (c) for whole countries, blue WF only; (d) for whole countries, combined blue plus green WFs; and (e) per capita, for baseline diets only, separated by blue and green WF. Countries are sorted by (a–d) baseline footprint or (e) blue WF. Due to space constraints, of the 140 study countries, only the following are shown here: (a, b, e) the 35 countries above the 75th percentile for whole country baseline footprint, and (c, d) the 14 countries above the 90th percentile for whole country baseline footprint.

intensive diets—have been vastly underrepresented in the literature (Appendix A, Table A1).

The scenario in which countries adopt the average baseline consumption pattern of high-income OECD countries (Figs. 6, 8a–d) isolates the effects of import patterns and COO on GHG and water footprints. Holding diet composition constant across the 140 study countries, the GHG and consumptive (blue plus green) water footprints associated with this scenario showed substantial variation (averaging 2.5 ± 0.9 metric tons CO_2e/capita/year and 1.5 ± 0.5 megaliters/capita/year, respectively).

A number of country governments, including Brazil (Ministry of Health of Brazil, 2014) and more recently Canada (Health Canada, 2019), have put forth dietary guidelines emphasizing predominantly plant-based foods. While this is a critical step toward aligning domestic consumption patterns with public health and ecological goals, countries' production and export patterns merit additional attention. Brazil, for example, was the top exporter of bovine meat (based on an average of 2011–2013 data) and was in the top quartile for GHG-intensity of bovine meat production (Fig. 3). Together with other major GHG-intensive exporters such as India and Paraguay, Brazilian bovine meat exports contributed to the large GHG footprints of diets in importing countries like Chile, Hong Kong, Kuwait, Venezuela, and Israel. In a hypothetical scenario in which the share of Hong Kong's bovine meat imports from Brazil came from Denmark instead, Hong Kong's per capita GHG footprint for the baseline pattern was 18% lower. While not necessarily feasible or desirable, this scenario further illustrates the importance of accounting for trade patterns and COO.

3.2.4. Per capita GHG footprints of whole diets

The countries with the most GHG-intensive baseline consumption patterns (Fig. 6)—and the greatest potential GHG reductions from shifting toward plant-forward diets—included those with the highest per capita intake of bovine meat (Argentina, Brazil, Australia), the most GHG-intensive bovine meat production (Paraguay, Chile; Fig. 3), and the greatest contributions of deforestation to the GHG footprints of diets (Paraguay, Chile, Brazil; Brazil is shown in Fig. 7). Deforestation accounted for 61% of the GHG footprint for the Paraguayan baseline consumption pattern, and over 10% of the GHG footprints for 32 countries' baseline patterns.

Over all 140 study countries, a theoretical shift to vegan diets reduced per capita diet-related GHG footprints by an average of 70%, relative to the baseline (Fig. 5a). Vegan diets had the lowest per capita GHG footprints in 97% of study countries. Given the low per-kilocalorie GHG footprints of most plant foods (Fig. S1), even substantial increases in consumption had only modest effects on GHG emissions of diets. For the US vegan diet, for example, scaling up plant foods recouped 100% of the calories and protein from animal foods with only 16% of the GHG emissions relative to the adjusted baseline (Fig. 7).

Relative to vegan diets, low-food chain diets (i.e., predominantly plant-based plus forage fish, bivalve mollusks, and insects) offer greater flexibility by allowing for modest animal product intake with comparable environmental benefits (Fig. 5). Low-food chain diets also met the recommended intake of vitamin B12 for adults (2.4 μg/day; Institute of Medicine Food and Nutrition Board, 1998) in 49% of study countries, illustrating that there may be ways to mitigate this potential limitation of plant-forward diets even without supplementation, at least for the general population.

Mostly plant-based diets were generally less GHG-intensive than lacto-ovo vegetarian diets, in part due to the relatively high GHG footprint of dairy (and eggs, depending on the basis of comparison; Figs. 2, S1–S3) and the reliance on dairy as one of only three food groups in the lacto-ovo vegetarian diet used to meet the protein floor (Fig. 1). This phenomenon was particularly notable for India (Figs. 6 and 7). In 95% of countries, two-thirds vegan diets were less GHG-intensive than lacto-ovo vegetarian (e.g., Figs. 6 and 7). Countries where this was not the case included those with some of the most GHG-intensive baseline consumption patterns (i.e., Paraguay, Chile, Argentina), largely because of the GHG-intensity of ruminant meat in those countries. In 64% of countries, the GHG footprints of no dairy diets were lower than those of lacto-ovo vegetarian diets (e.g., India and Indonesia, Fig. 7; also Fig. 6). In 91% of countries, the GHG footprints of low-food chain diets were less than half those of lacto-ovo vegetarian diets. These findings suggest populations could do far more to reduce their climate impact by eating mostly plants with a modest amount of low-impact meat than by eliminating meat entirely and replacing a large share of the meat's protein and calories with dairy.

3.2.5. Per capita water footprints of whole diets

Per capita blue WFs of diets (Fig. 8a, e) were in many cases largest in countries with 1) low annual precipitation, increasing reliance on irrigation for domestic crops; and 2) climatic factors such as high temperatures that contribute to high evapotranspiration rates, and thereby decrease crop water productivity (i.e., crop output per unit of water consumed). These included Iran, Egypt, and Saudi Arabia. Domestically-produced rice was among the top contributors in high-blue WF countries, four of which (Kazakhstan, Afghanistan, Pakistan, Iran) were also among the most blue water-intensive rice-producing countries (e.g., Fig. 4; rice WFs for all countries are provided in Mendeley Data input/item_footprints_by_coo). For blue WF reductions, the most impactful per capita dietary shifts were in Egypt, in part due to the high blue water intensity of Egyptian bovine meat and dairy.

For baseline consumption patterns, the consumptive (blue plus green) WF was highest for Niger (Fig. 8b, e), 98% of which was attributable to green water. Domestically-grown millet was the largest single contributor (40%) to the consumptive WF of the baseline consumption pattern. Niger had by far the highest per capita millet supply of any country, and was the 3rd largest producer and 8^{th} most water-intensive millet-producing country. The low water productivity of millet in Niger was attributable to low edible yield and high evapotranspiration rates. Inedible millet crop residues, however, provide fuel, construction materials, and livestock fodder (Sadras et al., 2009), illustrating how sociocultural and economic provisions of agricultural goods must be considered alongside ecological outcomes (see Section 3.3).

Potential reductions in per capita consumptive WFs from shifting to vegan diets were largest in Bolivia, Israel, and Brazil. Bovine meat, poultry, and dairy together accounted for over half of the consumptive WFs of the baseline consumption patterns in each of these countries. In Israel, for example, the per capita consumptive WFs of the low-food chain and vegan diets were 66% and 67% lower, respectively, than that of the baseline consumption pattern. Bolivia was the most water-intensive producer of bovine meat and the second for dairy, and most of the country's supply of these items was produced domestically. Bolivia also has a high prevalence of anemia (Development Initiatives, 2018), thus efforts to mitigate high WFs through dietary interventions must give this careful consideration.

For many countries, the blue WFs of low and no red meat, no dairy, and pescetarian diets were higher than those of baseline consumption patterns (Figs. 5a, 8a). These diets scaled up aquatic animals, of which the FBS items "Freshwater Fish" and "Crustaceans" were highly blue water-intensive when raised in ponds (Figs. 2, S1–S3). Contributions of aquatic animals to the blue WFs of baseline, low red meat, and no red meat diets exceeded those from terrestrial meat in 29%, 34%, and 69% of countries, respectively. In mainland China and Indonesia, for example, aquatic animals contributed 29% and 26%, respectively, to the blue WFs of baseline consumption patterns. In both countries, a substantial share of domestic fish production was from aquaculture (72% and 38%, respectively), predominantly for domestic consumption and not export (Belton et al., 2018). Replacing water-intensive pond-raised species with forage fish and bivalve mollusks, as in the low-food chain diet, could reduce both water and GHG footprints (see Section 3.3 regarding limits to increased aquatic animal intake).

Note that we did not have information about the shares of freshwater fish and crustaceans consumed in a given country that were farmed in ponds, so we made assumptions based on global production patterns (see Section 2.7.6). This method overestimates blue WFs of countries that source a large share of these species from wild fisheries or non-pond aquaculture, while underestimating blue WFs of countries for which the converse is true.

3.2.6. Targeting dietary interventions and whole-country footprints of diets

All else being equal, optimal interventions would promote dietary shifts in countries with large potential reductions in both per capita and whole country GHG and water footprint (acknowledging that “optimal” depends on a wide range of factors, including many not considered here; see Section 3.3). Based on shifting to a two-thirds vegan diet for purely illustrative purposes, only three countries—Brazil, the US, and Australia—were in the highest quintile for all four of the following criteria: greatest potential per capita and whole-country reductions in both GHG and consumptive water footprints (Fig. S4).

3.3. Limitations and opportunities for future research

There is much variability and uncertainty in accounting for post-farm gate activities (e.g., processing, transportation, retail) and soil carbon fluxes, and accordingly, they are rarely included in the scope of item footprint studies. Both were thus excluded from this study. We do not expect the former to affect our overall conclusions, as the majority (80–86%) of diet-related GHG emissions have been attributed to the production stage (Vermeulen et al., 2012).

Accounting for soil carbon sequestration has been shown to lower estimates of the GHG footprints of ruminant products, particularly those from management-intensive grazing systems (e.g., Pelletier et al., 2010; Tichenor et al., 2017). Further research is needed to measure the potential for soil carbon sequestration to reduce ruminant GHG footprints over a broad geographic and temporal scale, given it is time-limited; reversible; and highly context-specific based in part on soil composition, climate, and livestock management (Garnett et al., 2017). Conversely, the potential for soil carbon losses (e.g., from overgrazing or feed crop production) to increase ruminant GHG footprints should also be considered. Regardless of the uncertain role of well-managed grazing systems in carbon sequestration, the potential benefits for soil health, biodiversity, animal welfare, and other dimensions independent of climate change should also be taken into consideration. Apart from livestock production, carbon fluxes in crop and polyculture systems should also be further explored.

Aside from shifting consumption patterns, our study model holds other factors constant over time, including climatic conditions, population dynamics, food wastage, trade patterns, and the GHG- and water-intensity of production. Over the gradual course of changing diets, these factors will change in ways that are difficult to anticipate, e.g., as a result of rising incomes, evolving technology, changing trade policies, and economic feedback effects. Furthermore, we assume a proportional relationship between shifting demand and supply-side impacts, whereas the impact of dietary shifts on blue water conservation, for example, may be limited without policies promoting sustainable withdrawal rates (Weindl et al., 2017). Similarly, reducing animal product intake cannot reverse CO_2 emissions from deforestation unless land is taken out of production and reforested (Searchinger et al., 2018). Given their uncertain potential, dietary shifts should be complemented with other behavioral and policy interventions.

Further research is needed to examine dietary shifts in the context of social, economic, ecological, and agronomic feasibility, particularly in low- and middle-income countries (Kiff et al., 2016), as well as the effects on other health, social, and ecological measures not considered here (e.g., producers’ livelihoods, land availability, biodiversity, and eutrophication potential). Shifts to plant-forward diets, for example, must ensure target populations have sufficient physical and economic access to a variety of nutrient-dense plant-based foods. Agricultural systems would need to scale up production of fruits, vegetables, and proteins to meet the nutritional needs of the current population (KC et al., 2018), concurrent with a more equitable redistribution of available food. Dietary scenarios that increase aquatic animal consumption, meanwhile, raise concerns regarding depletion of wild stocks and ecological issues associated with increasing production of certain farmed species (Thurstan and Roberts, 2014). The feasibility of sustainable diets may further depend on how well proposed eating patterns align with historical and cultural context. Van Dooren and Aiking (2016) demonstrate a method for balancing several of these domains by simultaneously optimizing modeled diets for nutrition, climate change mitigation, land use, and cultural acceptability. Our use of baseline consumption patterns as a reference point helped to preserve countries’ eating patterns when modeling diets (Section 2.4); cultural receptivity could be further refined, however, by using national food-based dietary guidelines (FBDGs) to define criteria for healthy diets for individual countries, as in Vanham et al. (2018), rather than global recommendations (Section 2.4). Alternatively, or in cases where countries do not have FBDGs, this research could help define FBDGs that are healthy, sustainable, and culturally appropriate. Country-specific analyses that account for cultural acceptability could then be placed within the context of the planetary boundaries for food systems proposed by the EAT-Lancet Commission (Willett et al., 2019). The need to better characterize the impacts of, viability of, and strategies for shifting toward plant-forward diets, however, must be balanced against the preponderance of evidence calling for immediate action.

4. Conclusion

We evaluated nine plant-forward diets aligned with nutrition guidelines, specific to 140 individual countries, for their potential roles in climate change mitigation and freshwater conservation. Accounting for country-specific differences in over- and under-consumption, trade and baseline consumption patterns, and the GHG- and water-intensities of foods by COO can help tailor policy and behavioral interventions. Using this approach, we present a range of flexible options for each country that better align dietary patterns with public health and ecological goals, including viable alternatives for low- and middle-income countries that might otherwise adopt the consumption patterns of OECD countries.

Declaration of Interest Statement

None.

Contributions

B.F.K and S.R.C. developed the model with guidance and contributions from all co-authors; J.P.F. provided guidance and expertise on the modeling and analysis of aquatic animal footprints; M.M.M. and A.Y.H. provided guidance and expertise on water footprints and co-product allocation; S.D.P. and M.W.B. provided guidance and expertise on modelling healthy diets; A.P.S., B.F.K., R.E.S., and C.M.S. performed the search and standardization of item footprint studies; R.E.S. performed the literature review of other diet footprint studies; B.F.K. and R.E.S. wrote the manuscript; and K.E.N. and R.A.N. provided guidance and expertise on all facets of and supervised the project. All authors reviewed and contributed to manuscript drafts.

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Supplementary information

Supplementary figures, tables, and appendices related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gloenvcha.2019.05.010. Supplementary data are provided via Mendeley Data (Kim et al., 2019).

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