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The role of seafood in sustainable diets

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The role of seafood in sustainable diets

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J Zachary Koehn^{1,2} , Edward H Allison^{3,4}, Christopher D Golden⁵ and Ray Hilborn¹¹ School of Aquatic & Fishery Sciences, College of the Environment, University of Washington, Box 355020, Seattle, WA, 98195-5020, United States of America² Center for Ocean Solutions, Stanford University, 473 Via Ortega, Stanford, CA, 94305, United States of America³ School of Marine and Environmental Affairs, University of Washington, 3707 Brooklyn Ave NE, Seattle, WA 98105, United States of America⁴ WorldFish, Jalan Batu Maung, Batu Maung, Bayan Lepas, Penang 11960, Malaysia⁵ Department of Nutrition, Harvard T.H. Chan School of Public Health, Harvard University, 655 Huntington Avenue, Building 2, Room 329, Boston, MA, 02115, United States of AmericaE-mail: zkoehn@stanford.edu**Keywords:** aquatic foods, food system, environmental impact, nutrition, diversitySupplementary material for this article is available [online](#)**Abstract**

Recent discussions of healthy and sustainable diets encourage increased consumption of plants and decreased consumption of animal-source foods (ASFs) for both human and environmental health. Seafood is often peripheral in these discussions. This paper examines the relative environmental costs of sourcing key nutrients from different kinds of seafood, other ASFs, and a range of plant-based foods. We linked a nutrient richness index for different foods to life cycle assessments of greenhouse gas (GHG) emissions in the production of these foods to evaluate nutritional benefits relative to this key indicator of environmental impacts. The lowest GHG emissions to meet average nutrient requirement values were found in grains, tubers, roots, seeds, wild-caught small pelagic fish, farmed carp and bivalve shellfish. The highest GHG emissions per nutrient supply are in beef, lamb, wild-caught prawns, farmed crustaceans, and pork. Among ASFs, some fish and shellfish have GHG emissions at least as low as plants and merit inclusion in food systems policymaking for their potential to support a healthy, sustainable diet. However, other aquatic species and production methods deliver nutrition to diets at environmental costs at least as high as land-based meat production. It is important to disaggregate seafood by species and production method in 'planetary health diet' advice.

1. Introduction

As global human populations grow and become wealthier, demand rises on terrestrial and ocean environments as sources of foods and providers of other ecosystem services (Springmann *et al* 2018). Continued growth and development also places additional strain on our climate, and the resulting climatic changes will in turn influence regional food productivity (Godfray *et al* 2010). Our food systems primarily rely on land-based production of plants and animals, but wild capture fisheries and, increasingly, inland and marine aquaculture—the farming of fish shellfish and aquatic plants—are an important source of micronutrient rich foods (Seto and Fiorella 2017). Nevertheless, aquatic contributors to the global food system are often seen as peripheral, despite global fish

production ranked between poultry and beef (Troell *et al* 2014, Edwards *et al* 2019). A recent review finds that seafood is often excluded from food security and food systems research, and when included, seafood consumption is viewed as a tradeoff between positive health outcomes and overfishing concerns (Farmery *et al* 2017). When included in global assessments, all seafood—both wild capture and aquaculture—is often included as a single commodity despite the widely varying nutrient compositions (Hicks *et al* 2019) and environmental impacts of catching or rearing different seafood species and bringing them to market (Hilborn *et al* 2018). This is, in part, due to the fact that the research and policy agenda for fishery policy and food, nutrition and health policy run 'on independent tracks, with only loose and superficial links between them' (Hall *et al* 2013, p 8398). To

bring a more complete understanding of the potential role of seafood in healthy, sustainable diets, here we compare nutrient content and greenhouse gas (GHG) emissions—as a key indicator of environmental impacts—of major seafood species and production methods with land-based food production systems.

While most research and policy debate on the nutritional benefits of fish and shellfish has centered on protein and omega-3 fatty acids, many fish and shellfish may play a critical role in addressing deficiencies in other micronutrients such as vitamin A, calcium, vitamin B12, iron and zinc (Kawarazuka 2010, Golden *et al* 2016). These nutrients are often found in more bioavailable forms in fish and shellfish than they are in many vegetables, fortified staples, and food supplements (Bogard *et al* 2015, Thilsted *et al* 2016). For many countries facing nutrient deficiencies, finfish catches alone could provide all dietary micronutrient requirements for all people living within 100 km of the coast in those countries (Hicks *et al* 2019). Potential nutritional benefits of fish and other aquatic animals are not limited to coastal communities: inland capture fisheries production has increased each year, with most recent data indicating a 11.6 million metric tons (mmt) in 2018, and inland aquaculture is much larger than either marine aquaculture (30.8 mmt) or freshwater capture fisheries (12 mmt), producing 51.3 mmt in the same year (FAO 2020).

Given growing interest in the environmental sustainability of food production, and the known nutrient richness of seafood, a key question is then whether seafood provides an environmentally efficient way to supply essential micronutrients: does it have a place in ‘planetary health diets’ (Willett *et al* 2019)? This question can be addressed using life cycle assessments (LCAs), which provide a means to track inputs and outputs associated with different food commodities and production systems to compare the environmental cost, in this case, of supplying micronutrients to human diets (Garnett 2013). A 2017 meta-analysis of 369 published LCA studies across plant and animal-source foods (ASFs) found that plant-based foods had the lowest impact whereas ruminant meat had the highest, and seafood species ranged from moderately low (e.g. herring) to high (e.g. lobster) (Clune *et al* 2017). In 2018, Poore and Nemecek used existing LCA data to create a model to predict multiple environmental impacts at each node in the food supply chain, relying on thousands of datapoints from farms, processors, packaging firms, and retailers; it also found plant-based foods have impacts lower than the lowest impacts among ASFs (Poore and Nemecek 2018). A recent commission by the Lancet found a ‘planetary health’ diet consisting of raw plant-source foods a low to moderate amount of seafood and poultry, and no or a low quantity of red meat, processed foods, and starchy vegetables is

needed to achieve nutrition requirements and minimize a range of environmental impacts including GHG emissions, land use, and acidification (Willett *et al* 2019). Similar to Poore and Nemecek (2018) and unlike the more species-specific study by Clune *et al* (2017)—the Lancet Commission chose to report ‘fish’ and ‘crustaceans’ as broad categories. These three studies analyzed environmental impact in terms of overall volume (e.g. kg of food produced), and not in terms of specific nutrients. While aggregation may be necessary at a high level, results from seafood-specific LCAs suggest much information is lost by such grouping. Aggregation is also problematic given that seafoods are diverse in terms of production and in terms of micronutrient richness (Thilsted *et al* 2016, Golden *et al* 2021b). A meta-analysis of animal proteins finds wild-capture small pelagic fisheries performed best while industrial beef and catfish aquaculture performed worse (Hilborn *et al* 2018).

This research extends the work of Hilborn *et al* (2018) and Hallstrom *et al* (2019) to include products from land and marine ASFs as well as a selection of plants that have yet to be compared with the ASF literature. This work establishes a connection between nutrient content and environmental footprints to determine which animal-source protein most efficiently supply nutrients relative to their GHG emissions (mentioned throughout as ‘environmental impacts’). This work evaluates environmental tradeoffs in the production of macro- and micro-nutrients to improve decision-making toward more nutrient-dense food outputs that minimize environmental impact.

2. Methodology

2.1. Summary of datasets

We created an environmental impacts database including 1784 observations for 160 plant- and animal-based food products, originating from 415 databases and studies (table A1 available online at stacks.iop.org/ERL/17/035003/mmedia—see individual databases and studies in supplementary material). Environmental impact observations (which are exclusively represented via GHG emissions in this research) originated from two synthesis studies. Hilborn *et al* (2018) was the sole source of data, for all ASFs (terrestrial and aquatic), with the exception explained in Section 2.2, but only included a few major plant-based commodities (i.e. corn, rice, soy, tubers, and wheat). Because we wanted to compare across all major food groups, we sourced food impact data for plant products from Clune *et al* (2017). The Hilborn *et al* data did include some plant information for major plant-based commodities, which presented us with an opportunity to compare GHG emissions for raw products to ensure similarity in how the observations were collected and processed in these two synthesis studies (see appendix figure A1).

Data included in this analysis can be primarily classified as large-scale production systems embedded within the Western diet. This excluded smaller-scale food production systems that are either developing or may be commonly consumed elsewhere, many of which may be nutrient rich nutrition and have lower environmental impact (Hadjikakou *et al* 2019). A few of these transformative systems include insect-based proteins, seaweed aquaculture, and plant or lab-based protein alternatives. Products included in this analysis do not represent all traditionally consumed foods or those that are culturally appropriate. They also do not include all consumed foods; of special note they do not include highly processed foods.

Individual products were aggregated into 35 food groups to summarize impacts across broad food production sectors. These food groups were assigned general market categories (e.g. small pelagics constitute the small fish category which includes herring, sardines and anchovy). These food groups correspond to data available in global trade and commodity production statistics, rather than by sample size or taxonomy. For example, we separated corn from other seeds because it is a major commodity. In one case, this aggregation strategy led to three categories with observations representing many individual food products: fruit ($n = 37$), seeds and whitefishes (both $n = 12$). This also led to these groups having greater variation in nutrient richness and in their resulting environment-nutrition ratios at the food group level. The products within each of the food groups are specified in table A3. All methods related to standardizing environmental impact information, nutrient richness and the environment-nutrition ratio were all conducted at the individual product level. However, the optimization was run only on the 33 food groups. Please see the subsections below for further methodological details on these calculations.

2.2. Environmental impact standardization

For animal-based foods we converted all impacts to grams of edible product using conversion tables from Hilborn *et al* (2018). All environmental impacts were standardized to the farm gate/fish dock—including all impacts through to the end of production but not including impacts associated with transportation or consumption. It was also important to consider that some impacts were allocated to products on a mass-, economic- or energy-basis, and this may change how the environmental burdens associated with the creation of each product or its co-products (e.g. fish heads and fillets) were distributed. Observations originating in Clune *et al* (2017) only included mass-based allocation of impacts for raw product. Hilborn *et al* was not clear on how it treated mass versus economic- or energy-based allocation, so we returned to the Hilborn *et al* database and removed 24 studies that specified that the estimates were based on economic- or energy-based allocation. The remaining

studies either specified that the estimates were mass-based allocation based or were assumed to be so. In removing the information that was not mass-based, we also removed all data from two major commodified species: tilapia and pangasius catfish. In order to compare across all major terrestrial and aquatic groups, we added two additional sets of data that include tilapia and pangasius catfish estimates (Henriksson *et al* 2015, 2017). If there were co-products (e.g. the inedible parts of food used in fishmeal production) the impacts were either allocated by value of the co-products or all were assigned to the functional mass unit. If the system boundaries in the LCA extended beyond the farm gate/fish dock, we subtracted the post farm gate contribution estimated by Clune *et al* (2017).

2.3. Estimating nutrient production using a nutrient richness index

A nutrient richness index was used to capture nutrient concentrations across a diversity of critical nutrients. This builds upon environmental impact research focusing on impacts related to single nutrients (e.g. Hilborn *et al* 2018), by recognizing that the value of many foods is in their portfolio of multiple nutrients (e.g. FAO *et al* 2020). The nutrient richness index for a food product was calculated as the proportion of daily requirements for a nutrient met by a 100 g serving (Drewnowski 2009). We modified Drewnowski's method of calculating the nutrient richness index in two ways. The first was to add a combined value of DHA and EPA Omega-3 fatty acids—marine-based and often discussed as important contributors to maternal and childhood health—to the 'NR15' nutrient group calculated by Drewnowski (2009) using 15 nutrients. Nutrient composition profiles were downloaded from the USDA Food Composition database, including information on 43 nutrients across 213 food products (United States Department of Agriculture and Agricultural Research Service 2019). The only nutrient data that was not sourced from USDA was for pangasius catfish because it is not in the USDA database. This data was sourced from the Aquatic Food Composition Database (Golden *et al* 2021a). The second was to make these calculations focus exclusively on the nutrients 'to encourage' in Drewnowski *et al* (2009) and not the nutrients 'to limit': saturated fats, sodium or added sugar. In total, 12 beneficial nutrients were used (table A4). To calculate the nutrient richness index, we determined the individual richness of each nutrient in terms of 100 g servings (equation (1))

$$N_{p,n} = \frac{C_{p,n}}{D_n} \quad (1)$$

where nutrient richness $N_{p,n}$ is the proportion of the daily requirement of a given nutrient n per 100 g of edible product p met by that product's concentration of a given nutrient per 100 g. C is the concentration of

a given nutrient n per 100 g of edible product p , and D is the daily requirement required by adults for each nutrient n .

Once the nutrient richness scores were calculated for each individual nutrient, the scores were averaged across all 12 nutrients to create the nutrient richness composite index R_p for each individual food product (equation (2))

$$R_p = \frac{\sum_{i=1}^{12} N_{p,n}}{12}. \quad (2)$$

2.4. Methods to relate environmental impacts to nutrient production

Calculating the environmental impacts of nutrient production required the construction of a ratio of impacts to nutrient concentrations for each food. Environment-nutrition ratios were calculated as both impacts per nutrient richness composite index (equation (3)) and per individual nutrients (equation (4))

$$G_p = \frac{I_p}{R_p}. \quad (3)$$

G_p is the composite nutrient index for each product p , which is calculated by the impact of each product p divided by the composite nutrient richness index for that product. One environment-nutrition ratio was calculated for each combination of environmental impact and nutrient concentration for each product (e.g. three observations of GHG impacts per nutrient for corn meant three environment-nutrition ratios). Because the composite nutrient richness is an average of the 12 nutrient values, this ratio can be thought of as the environmental impacts required to meet the average daily recommendation across all included nutrients.

Environment-nutrition ratios were also calculated for specific nutrients where there are remaining concerns from the public health community regarding their deficiencies in diets around the world, namely zinc, iron, folate and vitamin A (Bailey *et al* 2015). We calculated individual environment-nutrition ratios for these nutrients and the others making up the *composite* index using equation (4).

$$S_{p,n} = \frac{I_p}{N_{p,n}}. \quad (4)$$

$S_{p,n}$ is the environment-nutrition ratio for each product I_p and each product's individual nutrient richness value $N_{p,n}$, calculated as the ratio of impact per 100 g of edible product to nutrient richness value.

2.5. Optimization of foods that minimize GHGs and meet dietary requirements

Alongside the consideration of the nutrient richness in individual foods, we also considered what selection of food groups would meet daily dietary requirements

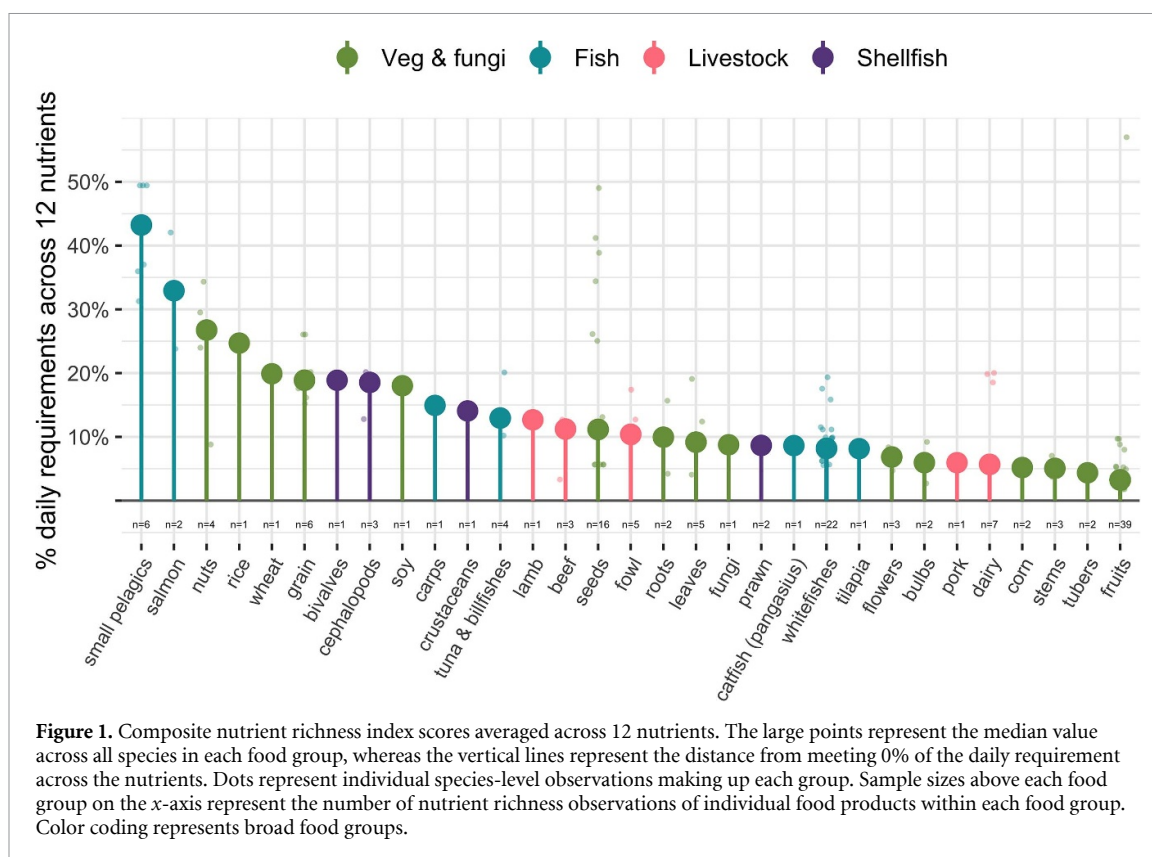
while minimizing GHG emissions. Note that we are only focused on the same set of nutrients used to create the nutrient richness index. These results do not recommend a comprehensive healthy diet but may inform the design of diets that meet the dual objectives of providing healthy and environmentally low impact nutrition. We used the GRG nonlinear function minimization routine in Microsoft Excel to find the combination of foods that would meet the daily requirements with minimum GHG impact. Three scenarios were included that reflect constraints in the model. Scenario 1 was unconstrained, allowing for any combination of food groups to determine which foods could meet dietary requirements while minimizing GHG emissions regardless of the quantity consumed or the number of calories. Scenario 2 placed a 2500 calorie constraint on the summed total of food groups to align with average energy intake needed for a 30 year old man (70 kg) or a woman (60 kg) with a moderate to high level of physical activity (See Willet *et al* 2019). Scenario 3 added a maximum of 200 g per day to each of the food groups in addition to the calorie constraint, in order to limit the consumption of any one food group to a reasonable intake.

Finally, we compared these results to the 'planetary health diet' (PH diet) that supports human health and sustainable food production to evaluate how a reference diet with only a single category for aquatic food (i.e. fish including shellfish) compares with the more disaggregated aquatic food groups used in this research (Willet *et al* 2019). The PH diet has simplified categories compared with the market-based categorizations of the food groups included in this research. As a result, we distributed the PH diet intake values evenly across the food groups used in this research. For example, 232 g of whole grain intake are recommended in the PH diet, which encompasses the food groups of grain, wheat, corn and rice in this research. We distributed the 232 g per day evenly across the four food groups, with a recommended intake of 58 g per day for each of grain, wheat, corn and rice. There were two food groups in this research that were more disaggregated in the PH diet—fowl and nuts. For fowl, we summed up the intake for chicken (29 g per day) and eggs (13 g per day). For nuts, we summed up the intake for peanuts (25 g per day) and tree nuts (25 g per day). For a detailed summary of how we distributed their food groups within the food groups used in this research, and for the file used to implement the optimizations, please see supplemental file 'food_group_optimization.xlsx'.

3. Results

3.1. Nutrient richness across foods

The nutrient richness index (equation (1)) reveals a considerable difference across food production groups. Among the most nutrient rich food product groups, salmon and small pelagic fish (e.g. anchovy,



herring, pilchards) rated highest, along with bivalves (e.g. mussels) and cephalopods (e.g. octopus). Some plant products—particularly nuts, rice and grain—were also nutrient-rich (figure 1). Beef, lamb and fowl (e.g. chicken) were the most nutrient-rich of the land-based ASFs. The lowest nutrient richness were prawns, catfish (*pangasius*), whitefishes, tilapia, plant flowers, bulbs, pork, dairy products, corn, stems tubers and fruits.

3.2. GHG emissions relative to nutrient richness

Plant-based foods had generally lower GHG footprint (i.e. GHG emissions needed to meet average nutrient requirements) compared to most ASFs (figure 2). But there were significant exceptions. Small pelagic fish (sardines, anchovies, herrings, mackerels) are the most abundant type of fish in global wild fish catches (FAO 2020) and are the most nutrient rich across all food groups. When considering GHG emissions associated with their production, only the median level of emissions for select plants (i.e. roots, grain, wheat, soy, nuts) is lower than for small pelagic fish.

Small pelagic fish, bivalves and carps all had GHG footprints much lower than land-based ASFs, where dairy and fowl had the lowest GHG footprint and pork, lamb and beef had the highest. Other than dairy and fowl, land-based ASFs had much higher median GHG footprints than most marine and aquatic ASFs. The GHG footprints of wild-capture small pelagic fish was 60-fold less than beef and 130-fold less

than wild capture prawns, which had the highest environment-nutrition ratio. While prawn production generally had very high GHG footprints, it varied depending on production sector: prawn capture fisheries had lower GHG footprints compared to prawn aquaculture.

Higher environment-nutrition ratios were driven either by high environmental impacts, low nutrient richness scores or a combination of the two. For example, dairy and pangasius catfish had lower average nutrient richness than many other ASFs. However, the environment-nutrition ratio for pangasius catfish is much higher because the food group's GHG emissions to produce 100 g of product is comparatively higher than dairy.

3.3. Environmental impacts of meeting dietary requirements of individual nutrients

When considering the GHG footprint across individual nutrients for a selection of two of the terrestrial and aquatic food groups with environment-nutrition ratios that were the lowest (i.e. roots, small pelagics), and highest (i.e. beef, prawns), we see the importance of specific environment-nutrition ratios that drive the nutrient richness indicator (Figure 3). For some nutrients, the lowest and the highest have equal impacts to meet the daily requirement for some nutrients (e.g. Magnesium), but for others, there are considerable differences (e.g. Vitamin A RAE is approximately $150\times$ higher for small pelagics than for roots). In still other cases, nutrients are not available for

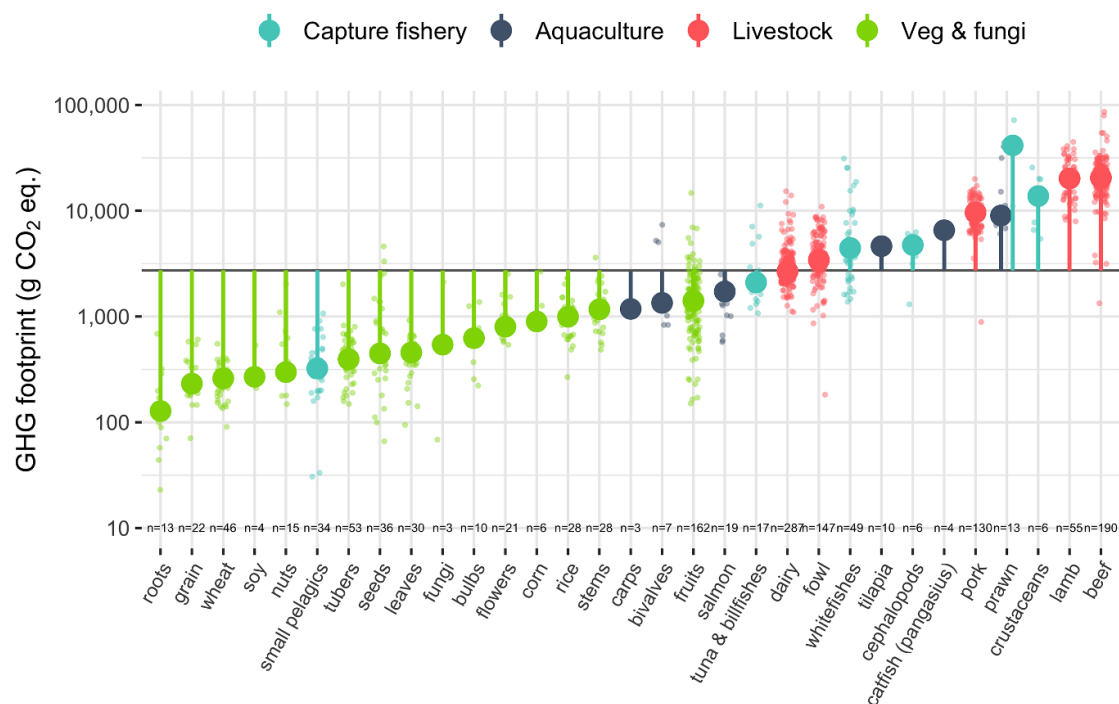


Figure 2. Greenhouse gas emissions relative to composite nutrient richness across major food groups. The y-axis is on a logarithmic scale. Lower values indicate that lower GHG footprints are required to meet the nutrient requirement average across 12 nutrients. The grey horizontal line indicates the median for all observations across the food groups (2725.10 g GHG emissions required to meet the nutrient requirement across 12 nutrients). The large points represent the median value across all species in each food group, whereas the vertical lines represent the distance from the median GHG footprint needed to meet 100% of the daily requirement across the nutrients across all food groups. Dots represent the individual species-level observations. Sample sizes above each food group on the x-axis represent the number of nutrient richness observations at species level within each food group. Color coding represent broad production systems.

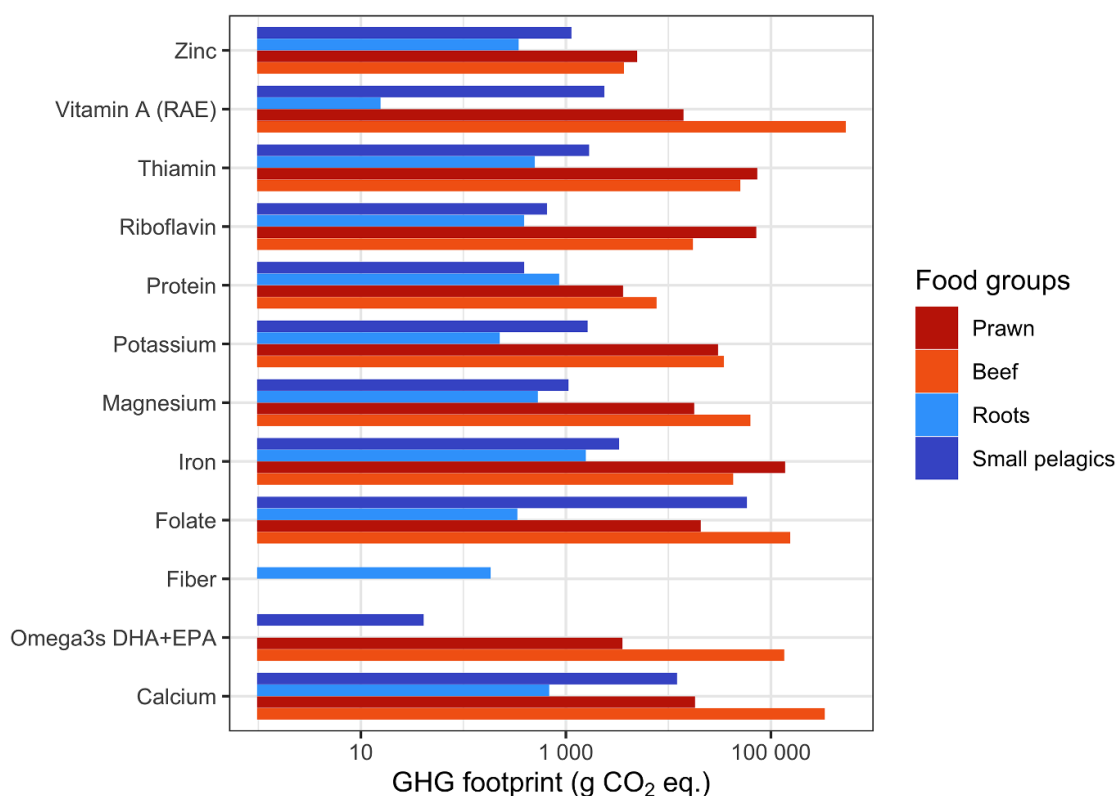


Figure 3. GHG emission impacts needed to meet daily requirements for individual nutrient richness across select food groups. The x-axis is on a logarithmic scale. Groups selected from the aquatic (darker shade) and terrestrial (lighter shade) food groups with the highest and lowest GHG footprints need to meet the daily requirement for each of the 12 nutrients included in the nutrient richness index. Missing data indicates no data for any food products within that species food group in the USDA nutrition database at the time it was pulled.

some food groups (e.g. dietary fiber is only found in plants and Omega 3 s DHA + EPA originate in marine sources, either in the wild or as part of feed formulations).

3.4. Portfolio of foods that meet dietary needs while minimizing GHG emissions

To meet daily dietary requirements for all 12 nutrients included in this research, the optimization revealed that a select group of foods minimize GHG emissions (table A2). In the unconstrained solution soy, plant leaves, wheat, and small pelagics make up the solution of meeting dietary requirements and minimizing GHG emissions without considering any constraints. Under Scenario 1, these food groups produced 451 g of CO₂ equivalents and only 1654 calories. When the calorie constraint was added in Scenario 2 to reflect daily consumption guidelines of 2500 calories, small pelagics, and plant leaves remained, but soy reduced in favor of grains and a large portion of bulbs, with a higher GHG impact of 488 g of CO₂ equivalents. When a limit is set on the volume of individual food groups that can be consumed per day to approximately two servings for each individual food group in Scenario 3, a still higher GHG impact of 578 g of CO₂ equivalents was reached by reductions in bulbs, grain, and the addition of nuts, dairy and roots. Finally, when distributing the scientific targets of the planetary health diet reference for the food groups in this data, we found a much higher GHG emissions than any of the 3 scenarios (1893 g of CO₂ equivalents), and only 1888 calories.

4. Discussion

Planning for our future requires a food system that produces enough to address malnutrition for growing populations while minimizing its global and regional environmental impacts. Decisions made on how food is produced, processed and distributed creates environmental impacts with consequences that range from exacerbating global climate change and its effects to finer-scale impacts on the surrounding environment like eutrophication. The results make clear that not all seafood is equal with respect to their environmental impacts and nutrient richness. Diversity with respect to species groups and production systems should be further recognized in future research and decision-making on the selection of food production systems that minimize environmental impacts and maximize contributions to food security and nutrition outcomes.

Across the development spectrum, nutrient-rich foods play an important role in addressing diet-based diseases and health risks caused by a transition to calorie-rich nutrient poor foods, a concern voiced in FAO's most recent *State of Food Security and Nutrition in the World* report (FAO *et al* 2020). A recent global study on environmentally sustainable diets

found that vegetable availability is insufficient to meet recommended consumption levels and this gap is only expected to widen (Mason-D'Croz *et al* 2019). As food production systems continue to reconcile their contributions to global environmental change, they also need to recognize the impact that these changes have throughout supply chains from decreasing nutritional quality of crops to increasing the need for additional cold storage infrastructure (Fanzo *et al* 2018). If regional supply solutions are not found, sustainable food systems in these areas will have to find alternative sources of comparably low environmental impact foods. Our results indicate that alongside some nutrient rich aquatic and marine foods—with much higher nutrient richness than many land-based ASF production systems—can help to meet this shortfall where production and/or supply is feasible. Any proposal to increase the supply of such healthful and low environmental impact seafood requires careful consideration for the governance and value chains of seafood provisioning. While there are substantial gains to be made by improved management (Hilborn and Costello 2018), wild fishery stocks will not alone meet growing, global demand for seafood. While farm-raised bivalves have high potential to contribute nutrient rich food at lower environmental impact than many other animals, but their production depends on regional growth potential and strong governance that guides financial and regulatory backing to support development (Davies *et al* 2019). Regulation can become an obstacle, as is the case for US aquaculture where environmental concerns can delay or stop permitting approval at federal, state or local levels (Knapp and Rubino 2016).

Our results also suggest that small pelagic capture fisheries hold promise as a component of 'planetary health diets'. One challenge limiting availability of small pelagic fish in the food system is the focus on conserving small pelagic fish for their predators; there is unclear evidence whether reductions in directed fishing of small pelagic fish has such benefit because of the variability in their abundance—even without fishing (Knapp and Rubino 2016). There are opportunities to direct more of the existing harvest of small fish towards human consumption; a large portion of the global harvest of small pelagic fish is converted into fishmeal and fish oil for use in aquaculture (Cashion *et al* 2017). Technical changes in aquaculture feeds such as insects, agricultural waste, and algae indicate that in the future more small pelagic fishes may be used directly as human foods (Costello *et al* 2019). A combination of supply chain interventions and marketing to increase consumer awareness and demand are likely required.

There were some limitations to this research that require discussion. While the environment-nutrition ratio approach is useful for comparison, it must be stated that these ratios will change as more LCAs

are published and as more nutrition information on species becomes available. The composite nutrient richness index, rather than the individual nutrient concentrations, is a useful summary metric when thinking of overall healthfulness of each food. However, from a public health nutrition standpoint an important consideration might be to find low impact foods that meet deficiencies in specific nutrients for a specific context. Here the preferred metric might be to focus on an individual nutrient exemplified in figure 3. Averaging across the 12 nutrients can hide low concentrations of nutrients within each food. For example, if dietary fiber is the concern, ASFs with high nutrient richness indices still will not be useful in meeting this need as fiber is found in plants. Relatedly, the focus of this research was on beneficial nutrients, and did not cover food safety concerns that exist among land and aquatic animal source foods. For example, toxins like methylmercury concentrate at higher trophic levels and in particular aquatic environments with adverse health outcomes particularly for pregnant women (Beckers and Rinklebe 2017). GHG emissions were the sole environmental impact in focus for this study, and it is important to note that these results may be cast in different light if other impacts are considered. For terrestrial systems, land use impacts may be similarly high for beef (Poore and Nemecek 2018). However, some plant-based foods that performed well in our analysis may have much higher impacts under metrics associated with land use. For example, land use for soy production may not only have high land use but has led to further biodiversity and deforestation impacts in Brasil (Garrett and Rausch 2016). This work was limited to impacts at the farm-gate or dock-side. Subsequent research should also consider impacts as these products move through the food chain, where we know that changes to processing, packaging, transport and food waste mitigation may have varied additional impacts (Poore and Nemecek 2018), but also present an opportunity for innovation. More research is required to extend the evaluation to these foods with respect to different types of environmental impacts, their use across the supply chain and whether scaling their production would provide a sustainable contribution to a more healthful food system.

Defining sustainable diets has received increased attention from the research and policy communities. The food combinations this analysis finds to deliver the lowest environmental cost per unit nutrient richness do not suggest a diet, but they do suggest a constellation of foods that contribute towards the creation of scenarios that may help shift consumers towards higher quality, nutritious plant-based food systems that can maintain a safe operating space across a suite of environmental impacts for aquatic and terrestrial foods. The environment-nutrition ratios for terrestrial foods largely uphold existing

research by Poore and Nemecek (2018), namely that plant-based foods have among the lowest GHG footprints across all foods. This work builds on those conclusions: with the exception of a few aquatic foods, plant-based foods perform better than ASFs when considering their impact relative to nutrient richness as well. This result also affirms the general conclusion that dietary guidelines recommending diets focused on plant-based foods and some fish are among the most healthful and sustainable (Springmann *et al* 2020), but takes a different approach that focuses more on malnutrition than on diet-based disease. Our results also support the general conclusions of EAT-Lancet Commission (Willett *et al* 2019); a majority of plant-based foods tend to have some of the lowest environmental impacts given their nutrient richness. Results of this research build upon the EAT-Lancet report by taking a finer resolution look at the fishery and aquaculture sector relative to livestock and plant-based agriculture. While the EAT-Lancet report does recommend fish generally, our more detailed analysis indicates that some capture fisheries and farmed shellfish have environmental impacts at least as low as many plants, and lower than most animal-source proteins. The optimization results further affirm this, and also reveal that theoretical optima will sometimes be challenging or impossible to apply in practice. True diet-based solutions must be affordable, diverse and culturally acceptable (Tuomisto 2019). It is our hope that wider recognition of the contribution of fish and shellfish to the food system will help drive fishery reform where overexploitation remains a concern in some parts of the world. In doing so, fisheries and aquaculture products that are nutrient rich and low in environmental impact can further contribute to food system planning that meets the objectives of the planetary health agenda.

5. Conclusion

Food production varies in terms of its environmental impact and its capacity to meet nutritional needs; this research combines these two factors, comparing products across plants and ASFs from terrestrial, capture fishery and aquaculture production systems, to identify foods and production system that provide nutrition at lower environmental impact. Foods sourced from plants as well as bivalve and carp aquaculture and small pelagic fisheries tended to have the lowest environmental impact given their nutrient richness to meet dietary requirements across a diversity of nutrients. In contrast, beef, pork, crustaceans, prawns and pangasius catfish had the highest environmental impacts given their nutrient richness. The contribution of plant-based foods discussed here supports the existing literature, but the potential role that certain species of fish can play in meeting dietary guidelines provides a novel insight to

identify nutrient-rich sources that not only combat malnutrition but also reduce environmental impacts of the entire food system.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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