Navigating sustainability and health trade-offs in global seafood systems

Abstract

Seafood is expected to play a key role in improving access to healthy diets while providing food products with relatively low rates of greenhouse gas emissions. However, both nutrients and carbon footprints vary among species and production methods, and seafood consumption is further influenced by price and consumer preference, such that it is unclear which species are best placed to provide low-emissions nutritious seafood. Here, we use seafood production data to assess the nutritional value, carbon emissions, sustainability, affordability, and availability of seafood available to UK consumers. Globally, most seafood products are more nutritious and emit lower greenhouse gases than terrestrial animal-source foods, particularly small pelagic fishes and bivalves that met recommended intakes for 2-3 essential dietary nutrients at the lowest emissions. For seafood products relevant to UK markets and consumers, Atlantic mackerel had the highest availability (i.e. landings) of all wild-caught UK seafood and lowest carbon footprint of all finfish, with one fillet portion exceeding recommended intakes of five nutrients (selenium, vitamins B12 and D). We found that price and sustainability of UK seafood, both factors in consumer demand, had considerable trade-offs with nutrients, carbon footprint, and availability. Farmed salmon, for example, were produced in large volumes but were relatively more expensive than other seafood, whereas highly nutritious, low-emissions farmed mussels had limited production volumes. The UK's seafood system is therefore not currently optimised to produce nutritious, low-emissions seafood in large amounts. Policies that promote local consumption of affordable species already produced in high volumes, such as mackerel, could improve intakes of nutrients that are deficient in the UK population at relatively low environmental cost.

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Introduction

Food systems must be transformed if countries are to achieve net-zero greenhouse gas emissions targets by 2050 (Clark *et al* 2020, Rockström *et al* 2020, Halpern et al. 2022), while also addressing growing malnutrition by improving access to healthy diets (Haddad *et al* 2016). Most animal-source foods, particularly livestock, have substantially higher greenhouse gas emissions than plant-source foods (Tilman and Clark 2014, Xu *et al* 2021), such that large-scale dietary shifts towards plants could substantially reduce food system emissions (Crippa *et al* 2021). However, animal-source foods provide concentrated, bioavailable sources of important dietary nutrients (calcium, selenium, fatty acids), some of which are not available in plant-source foods (e.g. vitamins B12, D) (Miller *et al* 2022), and deliver positive health outcomes for vulnerable populations, such as young children (Headey *et al* 2018). Transitioning towards low-emissions food systems while protecting access to healthy diets thus remains a significant global challenge (Rockström *et al* 2020), requiring analyses that assess both the nutritional value and environmental impact of diverse food products (Clark *et al* 2022).

Aquatic animals are increasingly recognized by the research community as nutritious animal-source foods that are critical to food and nutrition security (Hicks *et al* 2019, Belton and Thilsted 2014), produced for (relatively) low greenhouse gas emissions (Koehn *et al* 2022, Hallström *et al* 2019), and have potential to sustainably contribute to growing global food demand (Costello *et al* 2020, Béné *et al* 2015). Seafood is a rich source of protein and essential micronutrients, produced locally (Thilsted *et al* 2016) and traded globally (Gephart and Pace 2015) via capture fisheries and aquaculture that are both expected to have key roles in transitioning towards sustainable global food systems (Costello *et al* 2020, Naylor *et al* 2021). The carbon footprint (Gephart *et al* 2021, Parker *et al* 2018, Hilborn *et al* 2018) and nutrient content (Hicks *et al* 2019, Golden *et al* 2021) of seafood, however, vary considerably among species and production methods. For example, capture fisheries for crustaceans can produce 40x more greenhouse gas emissions than those catching small pelagic finfish (Parker *et al* 2018), whereas seafood farmed using feeds and requiring land conversion, such as shrimp, tend to perform poorly compared to unfed products that have negligible production emissions (MacLeod *et al* 2020). Nutrient content of these products also vary among species (Hicks *et al* 2019, Bernhardt and O'Connor 2021), and comparative analyses have shown that small pelagic fishes are among the most nutritious and lowest emissions seafood globally (Koehn *et al* 2022, Hallström *et al* 2019, Bianchi *et al* 2022). However, the potential for low-emissions seafood products to contribute to nutritious and climate-friendly diets will depend on their relative affordability (Headey and Alderman 2019) and availability to consumers (i.e. production and trade) (Nash *et al* 2022), which are rarely integrated into seafood carbon assessments (Ziegler *et al* 2022). It therefore remains unclear which seafood species can contribute to nourishing, low-emissions diets, within local contexts, and how current seafood systems could be shaped to achieve these goals.

Here, we compare the nutrient density and greenhouse gas emissions of 106 seafood products landed at fishing ports or produced at farm gates, and place these in context of availability (i.e. production and apparent consumption), affordability, and sustainability of seafood consumed in the UK. We use the UK as a case study because it has a productive and diverse seafood supply (Jennings *et al* 2016), high rates of animal-food consumption (Miller *et al* 2022), but long-term declines in seafood consumption (Franklin 1997, Watson 2022) and population-level deficiencies in nutrients that are concentrated in fish (Derbyshire 2018). The UK produces seafood through domestic fisheries landings (pelagic, demersal and shellfish species) and a large aquaculture sector dominated by Atlantic salmon (Garrett and Caveen 2018), while imports of salmon, cod, tuna and shellfish consistently exceed

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exports (Jennings *et al* 2016). These datasets are used to identify fish and invertebrate species low-emissions, affordable and nutritious, thus providing insights into how seafood could be harnessed to reduce food system carbon emissions while increasing supply of healthy animal-source foods.

Results & Discussion

Carbon footprint and nutrient density

We first assess associations between emissions and nutrients for the global database of 106 seafood products and 98 fish and invertebrate species. All seafoods had a higher nutrient density than other animal-source meats, and their greenhouse gas emissions were similar to chicken, pork and dairy products, but only 25% the carbon emissions of beef and lamb (Fig. 1A). Small pelagic fish such as herrings, sardines and anchovies, and wild Pacific salmon species such as pink and chinook, were the most nutritious and lowest-carbon fishes (Fig. S1), reflecting the low greenhouse gas emissions per unit catch of pelagic fisheries (Parker *et al* 2018, Parker and Tyedmers 2015). Invertebrate seafoods ranged from highly nutritious farmed mussels with negligible emissions output to crustaceans such as prawns and lobsters that are caught by high-emissions fisheries (average 11.6 kg CO_2-eq per kg seafood). After accounting for expected processing and waste from seafood, small edible portions in products such as scallop (12%), lobster (25%) and mussel (26%) further raised emissions from crustaceans (Fig. S2).

Placing these values in context of recommended sustainable diet guidelines (EAT-Lancet, Willett *et al* 2019), a 100 g seafood portion would account for between 5% (small pelagic fish) and 85% (crustacean) of the daily greenhouse gas emissions per person (Kovacs *et al* 2021). As noted by several recent global seafood analyses (Hallström *et al* 2019, Koehn *et al* 2022, Bianchi *et al* 2022), nutrient and CO_2-eq estimates averaged across wild and aquaculture obscured differences among species and production methods, with particularly large variation in greenhouse gas emissions among wild invertebrate fisheries and farmed fishes (Figs. 1B, S1). Such variability can be used to identify performance gaps (Gephart *et al* 2021), and here suggests that shifting production towards species with lower carbon emissions, within each taxonomic group, could still promote supply of nutritious seafood.

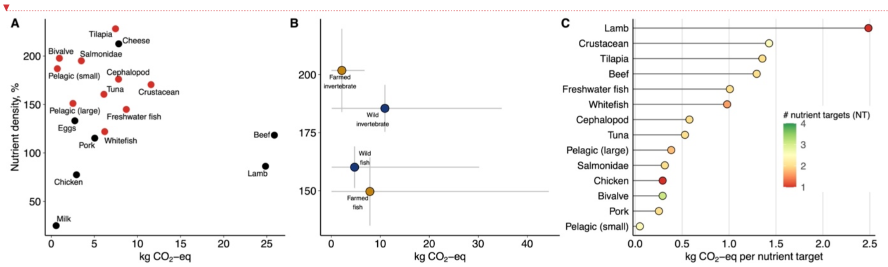

Figure 1 | Nutrient density and greenhouse gas emissions of global seafood products. A) The mean nutrient density and greenhouse gas emissions produced, for common seafood groups (red, live weight), terrestrial animal-source meat (black; beef, sirloin steak; chicken, average meat; lamb, mince; pork, mince) and dairy (black), B) shows the mean and range of values of farmed and wild-caught fish and invertebrates. C) is the greenhouse gas emissions per nutrient dietary target (averaged across species), coloured by the number of nutrient targets in a 100 g edible portion. Emissions were thus

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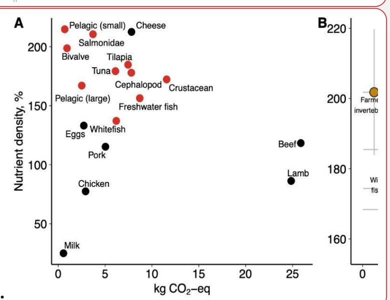

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generated by live weights in A and edible weights in C. Nutrient density (A, B) and targets (C) are recommended intakes of calcium, iron, selenium, zinc and omega-3 fatty acids for adults aged 18-65 (Drewnowski *et al* 2015). Animal-source foods (beef, chicken, lamb, pork) are included for comparison using CO_2 values from (Clune *et al* 2017) and nutrient values from (Widdowson n.d.). See Fig. S1 for the nutrient density and greenhouse gas emissions of each seafood product, Fig. S2 for emissions corrected by edible portion, and Fig. S3 for greenhouse gas emissions per nutrient dietary target of each species.

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Next, we combined nutrient density and greenhouse gas emissions estimates to quantify the emissions per recommended nutrient target (NT) in a single seafood portion (100 g) (Bernhardt and O'Connor 2021), and thus evaluate the potential for low-emissions seafoods to contribute to recommended intakes of specific nutrients. Across global seafood products with emissions data, wild-caught small pelagic fishes and farmed bivalves had the lowest emissions per NT, with a 100 g portion providing recommended intake for 2-3 nutrients at less than 0.3 kg CO_2-eq per NT (Fig. 1C). All seafood products reached at least one NT (selenium and/or omega-3 fatty acids), with the most nutritious seafood also reaching NTs for iron (e.g. bivalves) and zinc (pelagic fishes, crustaceans) (Fig. S3). Other animal-source foods only reached NTs for selenium (beef, chicken, pork) or zinc (beef, lamb, pork). In crustacean and livestock products, low nutrient content across multiple nutrients combined with high carbon footprints caused some crustaceans (e.g. Norway lobster, 3.1 kg CO_2-eq per NT), beef (1.3) and lamb (2.5) to have the highest emissions per NT for animal-source foods in our analysis (Fig. 1C, Fig. S3). High content of selenium and zinc in livestock and poultry is similar to most seafoods but for a far higher carbon footprint.

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Nutrient content and carbon footprint of UK seafood production

We compiled seafood production data for the UK (Fig. S4), where demand for wild and farmed seafood is declining (Seafish 2019b) and population-level intakes of nutrients concentrated in seafood are suboptimal (Gibson and Sidnell 2014, Derbyshire 2018). Seafood production was defined as the combined seafood available annually from total landings at UK ports, aquaculture in UK fish farms, and imported products. We also extracted data on five additional nutrients (iodine, vitamins A, D, B12, and folate) from UK and Norwegian food tables (Widdowson n.d., Norwegian Food Safety Authority 2021) that are concentrated in seafood (but were unavailable for all species in our global database, Fig. S1). Almost all seafood products provided 4-5 nutrient targets for less than 0.5 kg CO_2-eq per target, with pelagic fishes (skipjack tuna, herring) and bivalves (mussels) containing the most nutrient targets at lowest carbon emissions (Fig. S5). These seafood species could therefore contribute to alleviating population-level inadequate nutrient intakes at lower carbon cost than other animal-source foods.

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In the UK, one in two women are deficient at least one essential micronutrient (Stevens et al. 2022), with high deficiency rates for selenium (50%), vitamin D (22%), iron (21%), and folate (19%) (Derbyshire 2018, Stevens et al. 2022), all of which are concentrated in low-emissions seafood already available to consumers. For example, Atlantic mackerel had the lowest carbon emissions and highest nutrient density, providing over 100% the recommended intakes of selenium, vitamins B12 and D, 69% of omega-3 fatty acids, and 19% of iodine, for 0.25 kg CO_2-eq (Fig. 2A,C). Furthermore, 91% of UK children between 18-35 months are estimated to have inadequate dietary vitamin D intakes (Gibson and Sidnell 2014), yet a child's portion (40 g) of herring or mackerel contains 43-57% of the reference vitamin D intake (RNI) for children between 1 and 3 years old. These low-emissions wild-caught fish thus provide similar or greater nutritional benefits than other animal-

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source foods (RNI: beef = 30%, chicken = 5%, lamb and pork = 46%) at far lower greenhouse gas emissions. Oily fish such as mackerel, salmon and herring also contain toxic dioxin-like compounds that can produce negative health effects (Nøstbakken *et al* 2021), though risks from high oily fish consumption may be outweighed by their health benefits (Tuomisto *et al* 2020). Policies recommending future seafood consumption will nevertheless require guidance from both fisheries scientists and health professionals.

The potential for low-emissions seafood to contribute to healthy diets, however, also depends on its relative availability for domestic consumption, and consumer preference for those products (Zander and Feucht 2018, Parodi *et al* 2018, Jennings *et al* 2016). In the UK, four wild fish species (cod, haddock, mackerel, skipjack tuna) and farmed Atlantic salmon accounted for half of total available seafood in 2019 (Fig. S4). These top five species had similar average nutrient densities (284-410%, average = 350%) and carbon footprints (0.25-3.95 kg CO_2-eq, average = 2.6) (Fig. 2). Mackerel had the lowest carbon footprints of any wild-caught species and exceeded recommended intakes for iodine, selenium, omega-3 fatty acids, and vitamins B12 and D (Fig. 2). Promoting access and consumption of mackerel in the UK could improve diets with relatively low environmental impact, although currently the UK exported ~43% of its available mackerel (i.e. imported and landed) in 2019 (Fig. S6), limiting its potential as a locally produced, low-emissions nutritious food. Nutritious and low-emissions seafoods often had low apparent consumption relative to their total production (e.g. herring, mackerel) (Fig. S6), perhaps reflecting limited consumer appeal of some species and products. Outside these five high-production species, UK seafood produced in lower volumes had more diverse CO_2 emissions and nutrient density, including the highest (Norway lobster and wild-caught shrimp species) and lowest emissions for capture fisheries (mussels and Atlantic herring) (Figs. 2, S1).

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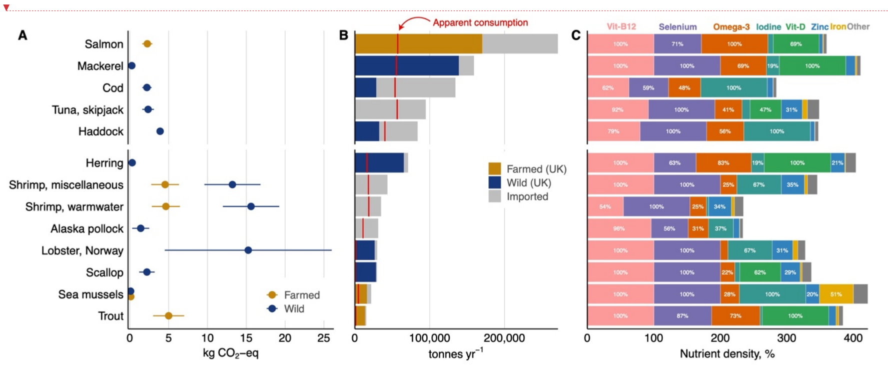

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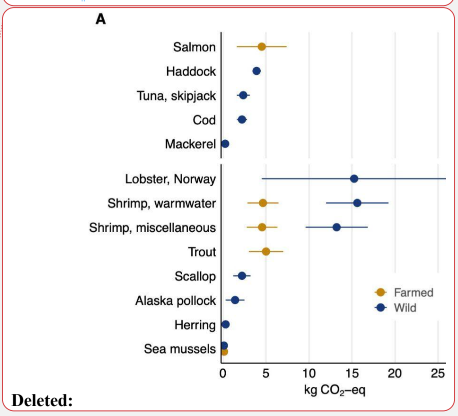

Figure 2 | Carbon footprint, production, and nutrient density of the top 90% of landed, farmed, and imported seafood products in the UK. A) CO_2 emissions per kg live weight seafood (± minimum and maximum), for wild and farmed products. B) Annual production of landed (UK), farmed (UK), and imported products in 2019, with red lines indicating apparent consumption by UK population (total production – exports, corrected for edible portion). C) Nutrient density scores across ten nutrients, based on recommended daily adult (18-65 years old) intakes for vitamin B12 (pink), selenium (purple), iodine (turquoise), omega-3 fatty acids (orange), vitamin D (green), zinc (blue), iron (yellow), and calcium, vitamin A, and folate (‘Other’, grey). See Fig. S7 for nutrient density calculated for five nutrients used in the global analysis in Fig. 1. Data on wild vs. farmed sources for

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imported and exported seafood were unavailable, and farmed production estimates are the average annual value across 2015-2018.

Sustainability and affordability of low-emissions nutritious seafood

Consumer demand for seafood in the UK is primarily influenced by price, with consumers favouring more affordable products (Seafish 2019a). Across Western Europe, preference for sustainable products is also a key influence on consumer behaviour (Menozzi *et al* 2020), as reflected by the rapid growth in seafood eco-labels (Roheim *et al* 2018). Indeed, low-emissions nutritious seafoods can contribute to healthy diets where they are affordable (Springmann *et al* 2021), and sustainable ecolabels can both promote consumption of certain seafood products (Honkanen and Young 2015, Jacobs *et al* 2018) and incentivize rebuilding of certified stocks (Gutiérrez *et al* 2012). We assessed these factors by compiling data on average price (GBP per kg) (Watson 2021) and (perceived) sustainability of seafood consumed in the UK, as defined by a ratings scheme designed for UK consumers (The Good Fish Guide) (see Methods).

Wild-caught seafood was, on average, cheaper than farmed seafood, owing to the dominance of farmed Atlantic salmon in domestic seafood production, which is associated with (relatively) higher prices (Fig. 3, Fig S8). Average sustainability ratings were similar between wild-caught and farmed seafood, but varied considerably between species (Fig. 3) and production methods (Fig. S8). Sustainability of wild-caught seafood was particularly variable, owing to spatial variability in stock status of species such as cod and herring (Fig. S8B). No species maximised all five desirable variables, underlining existing trade-offs between production, carbon footprints, price, nutritional value, and sustainability. These trade-offs reveal limitations of certain production systems (e.g. high emissions of Norway lobster) but also highlight potential for improving the environmental performance of high-volume foods (e.g. farmed salmon), exploitation of overfished stocks (e.g. cod), and the production of nutritious future foods (e.g. mussels) (Parodi *et al* 2018). Alaska pollock was the most affordable and sustainable seafood product for UK consumers but had relatively low availability (i.e. imports), suggesting that increasing Alaskan pollock imports could improve supply of affordable low-emissions seafood in the UK.

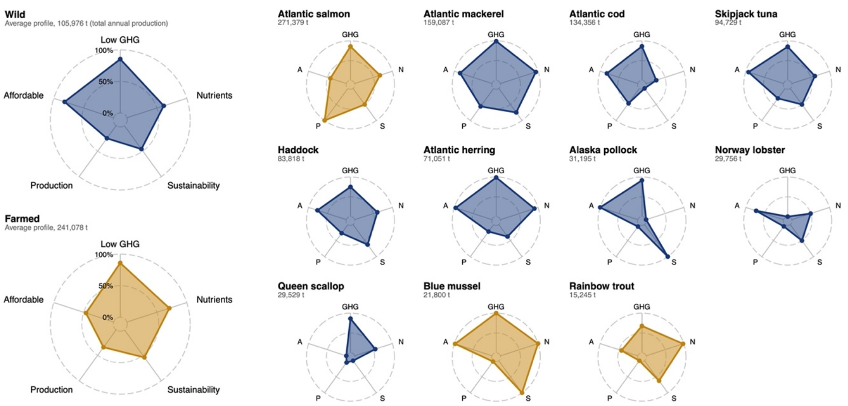

Figure 3 | Blue food profile of 11 major UK seafood products. Radar plots show the average carbon footprint (live weight kg CO_2-eq, inverse), nutrient density (10 nutrients), sustainability rating

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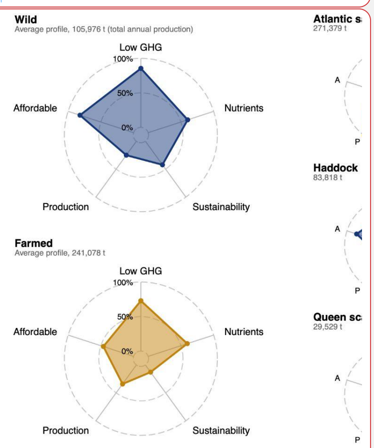

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(Good Fish Guide), production volume (annual tonnes), and price (GBP per kg, inverse) for wild-caught species and farmed species on average (A), and by product (B). All variables are scaled between 0-100%, and CO_2-eq and price are scaled to their inverse (i.e. 100% is the least CO_2-eq use and lowest price), such that species with the largest radar areas are low-emissions, nutritious, sustainable, high-production, and affordable. For average wild/farmed seafood (A), kg CO_2-eq, nutrient density, sustainability and price are mean values weighted by annual production among species.

Nutritious, cheaper, and low-emissions wild-caught fishes such as mackerel and haddock had high sustainability ratings (Fig. S8B), due to use of low-impact fishing gears (pelagic trawls) and low number of overfished stocks. Indeed, fisheries assessments show that low-emissions UK fisheries have steadily improved stock status since 1990, with high stock biomass and all mackerel stocks and 30% of herring stocks recently fished within sustainable levels (Fig. S9). These trends underline the effectiveness of fisheries management in rebuilding depleted fish populations when harvest control rules are implemented (Melnychuk *et al* 2021), and thus the benefits to food supply when stocks are sustainably fished (Costello *et al* 2016, Jennings *et al* 2016). Bringing the remaining overfished (30%) UK-sourced stocks within sustainable limits would therefore improve domestic supply of nutritious low-emissions food to UK consumers, and also reduce greenhouse gas emissions from fishing vessels by improving fuel use per unit catch (Hornborg and Smith 2020). Further gains in nutritious seafood production could be achieved by incorporating nutrient-based reference points (e.g. Maximum Nutrient Yield) into fisheries assessments that assess strategies for enhancing nutrient-rich catches. In North Sea fisheries, for example, nutrient yields could be increased by prioritising long-term catch of resilient and nutritious species such as herring and sprat (Robinson *et al* 2022).

UK aquaculture was less diverse than its capture fisheries, with domestic and imported Atlantic salmon together representing 62% of available farmed seafood. Sourcing low carbon-emissions inputs to aquaculture feeds, such as avoiding inputs associated with land-use conversion (Ziegler *et al* 2013) and improving feed conversion ratios (MacLeod *et al* 2020) would have significant benefits for improving UK aquaculture emissions. In contrast, farmed mussels were the highest-ranking seafood in 4 of 5 categories, but had the lowest production volume of all top 12 products (Fig. 3). Enhancing bivalve production and consumption globally has been proposed as a means of increasing global food supply with minimal environmental impacts (Willer and Aldridge 2019), and could contribute to production of more nutritious farmed seafood in the UK (Willer *et al* 2022). However, increasing prevalence of disease, toxic algal blooms and extreme weather has caused declines in EU mussel production (Avdelas *et al* 2021) and, in the UK, several additional factors have hindered marine aquaculture expansion, including competition for coastal space and poor water quality (Cappell 2020).

Reductions in livestock consumption, particularly beef, through demand-side policies have been proposed as a means of improving dietary health while reducing food-system carbon emissions (Bajzelj et al. 2014, Springmann et al. 2020). However, in the UK, seafood products are the most high-value protein food, above red meat and chicken (Watson 2021), while seafood retail prices increased by 31% from 2010 to 2020, exceeding general inflation (21%, Consumer Price Index) and terrestrial meat (11%) (Department for Environment, Food and Rural Affairs 2022). This likely contributes to long-term declines in seafood consumption, particularly for poorer households and younger age groups (Watson 2021, 2022). The UK's capacity to transition towards low-carbon animal-source foods is thus limited by low affordability of desirable high-volume seafood, such as salmon (£17.01/kg) and cod (£8.61/kg), and lower appeal of more affordable products (~£5.60/kg: Atlantic herring, farmed mussels). Positioning seafood as 'climate smart' will depend on the

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availability of nutritious, low emission products that offer consumers value for money compared to other proteins. This could be incentivised directly through increased production of low cost species, but also indirectly through food labelling, education campaigns, and taxation (Springmann et al. 2021).

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Collectively our findings suggest wild caught pelagic fishes and farmed bivalves have the greatest potential to be sustainable, nutritious, and low-emissions animal source foods, corroborating previous research (Hallström *et al* 2019, Koehn *et al* 2022, Bianchi *et al* 2022). By placing nutrient and carbon footprints in the context of seafood production volumes, we also reveal opportunities for transitioning seafood systems towards low-emissions, healthy foods. Information on long-term patterns in supply, affordability, sustainability, and consumption will develop deeper understanding of the drivers of seafood systems, and thus inform efforts to promote low-emissions seafood consumption. We expect our UK case study to be representative of seafood products in other high-income countries in the Global North where seafood sectors supply both wild-caught (e.g. whitefish, pelagic species) and farmed seafood (e.g. Atlantic salmon). In these countries, policies that support less well-developed sectors (e.g. farmed mussels) could reduce food sector emissions, while policies that help inform consumer choice of existing products (e.g. expanding certification schemes to include carbon emissions (Madin and Macreadie 2015)) could nudge consumers towards low-emissions, nutritious seafood (Bucher *et al* 2016).

Methods

Carbon footprints and nutrient data

We extracted estimates of greenhouse gas emissions relative to live weight wild-caught or farmed seafood from data modelled in the Seafood Carbon Emissions Tool (Monterey Bay Aquarium Seafood Watch and Dalhousie University) (Seafood Watch). This dataset was initially compiled to focus on seafood products relevant to the United States, but overlaps substantially with key species for other regions. Modelling underpinning emissions estimates was based on reported fuel use intensity (L/t) values for marine fisheries (Parker *et al* 2018, Parker and Tyedmers 2015), including emissions associated with bait use (e.g. tuna longlines, lobster traps). Emissions from aquaculture production were estimated with Monte Carlo analyses based on data extracted from published life cycle assessments and other sources. Input parameters accounted for consistently recognized drivers of greenhouse gas emissions in culture systems for which data were available across species and systems: feed conversion ratios, general feed composition, feed ingredient impact factors, rates of on-farm energy use, relative use of electricity or fuels, and impact factors for fuels and country-specific electricity grids.

This database contained greenhouse gas estimates for 98 fish and invertebrate species, representing 151 seafood products at the point of production (i.e. fishing port or farm gate), standardised as CO_2 equivalents per kg of seafood (kg CO_2-eq). A seafood product was one species produced by a specific production method (e.g. capture: longline, trap, trawl; farmed: pond, cage, net pen), and each species-method combination had median values and lower and upper limits of carbon emissions (25th and 75th quantiles). In cases where production was heavily skewed towards certain production systems, those systems were selected for inclusion in further analysis, excluding uncommon production methods (e.g. recirculating systems producing Atlantic salmon). These data were used to generate the range of expected greenhouse gas emissions produced by wild and farmed seafood products (Table S1). Most species had multiple emissions estimates collated across studies of different seafood

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production methods and locations, and we did not consider emissions generated in distribution, transport, and processing of seafood products. Our carbon footprint analysis thus represents the potential emissions generated by seafood production at port (capture fisheries) or farm gate (aquaculture), per kg of unprocessed fish or shellfish. By addressing emissions up to the point of landing or harvest, these estimates thus omit potentially important sources of emissions (e.g. distribution of products), and are insufficient for broad-scale carbon footprint modelling (e.g. biogenic emissions and land-use change emissions from converting mangroves for pond culture). However, this database provided a methodologically consistent approach among diverse fish and invertebrate species, and sufficient resolution of data to differentiate between related species. We estimated the minimum and maximum kg CO_2-eq for each species, and the midpoint of those values, separately for wild and farmed (n = 106 seafood products), and for related species groups (e.g. bivalves, whitefish, small pelagics) (n = 10 seafood groups) (Table S1). These values capture the range in species-level, live weight emissions between wild-caught and farmed seafood, across diverse production methods.

Nutrient data were extracted from Fishbase (Froese and Pauly 2022), providing estimates of calcium (mg), iron (mg), selenium (µg), zinc (mg), and omega-3 fatty acids (g) per 100 g of muscle tissue. Invertebrate nutrient content were the genera- or family-level mean nutrient concentrations from the FAO/INFOODS database of 195 samples of 45 species (FAO 2016, Rittenschober *et al* 2016). We estimated the nutrient density of each seafood product, defined as the combined contribution of a 100 g portion to recommended daily intakes of all five nutrients (Drewnowski *et al* 2015, Hicks *et al* 2021), based on nutrient reference values for adults aged 18-65 (FAO/WHO Expert Consultation on Human Vitamin and Mineral Requirements 2004).

We visualised nutrient density and greenhouse gas emissions (kg CO_2-eq) in a biplot alongside values for terrestrial animal-source foods, including dairy (cheddar cheese, whole eggs, semi-skimmed milk) and livestock (beef, sirloin steak; chicken, average; lamb, mince; pork, mince), based on a meta-analysis of carbon emissions data in (Clune *et al* 2017) and nutrient values in UK food composition tables (Widdowson n.d.). For carbon emissions, we used median values for each product, corrected to represent emissions from farm to farm gate (using Table 2 in (Clune *et al* 2017)). Note that terrestrial meats were per kg of bone free meat whereas seafood values were per kg of unprocessed whole fish. We then combined these metrics to measure the greenhouse gas emissions (kg CO_2-eq) per nutrient target of each terrestrial animal-source food and seafood product, following Bernhardt and O'Connor (2021). These emissions estimates were corrected to reflect the edible fraction of each species (Seafood Watch). Edible fractions were initially derived the UN Food and Agriculture Organization (FAO 1989) as well as from multiple government-, industry-, and NGO-sourced datasets (P. Tyedmers *pers. comm.* 2017). Adjusting for edible fraction allows for emissions to be communicated relative to the edible unit against which nutritional values are also communicated, and accounts for variation in yield of edible product among species of fish and shellfish. This metric thus expresses the greenhouse gas emissions required to meet one dietary target, based on recommended adult intakes (18-65 years old) contained in a 100 g edible portion.

Low-emissions potential of UK seafood

Next, we placed carbon footprint and nutrient density scores in the context of seafood production (Ziegler *et al* 2022), using the UK as a case study. We compiled annual landings, imports, exports, and aquaculture data for all UK seafood products from government databases (https://www.gov.uk/government/collections/uk-sea-fisheries-annual-statistics), Seafish (https://www.seafish.org/insight-and-research/market-supply-data-and-insight/), and the European

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Commission (https://stecf.jrc.ec.europa.eu/reports/economic/-/asset_publisher/d7Ie/document/id/287169). For each species group, we combined landings, import and export data for 2019 with the average annual aquaculture production across 2015-2018 (2019 data were unavailable), and matched these products to their average estimated carbon footprint and nutrient density. Where appropriate, species were combined into groups that aligned with commonly used product names (e.g. scallops, trout, shrimp). We estimated the annual seafood production available to the UK (sum of landings to UK ports, aquaculture produced in UK farms, and imported seafood), and apparent consumption of seafood by UK consumers (total production – exports, corrected for edible portion). These metrics quantify the composition and volume of seafood available to the UK per year, based on live weight production in 2019. Carbon emissions estimates were unavailable for farmed scallop, though this product contributed <1% of total UK scallop production (9.25 *t*).

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We estimated the kg CO_2-eq and kg CO_2-eq per nutrient target of all products that represented the top 90% of seafood availability in the UK. We used carbon emissions data that represented the dominant production method for each species (Table S2), and thus capturing key impact drivers of UK seafood emissions (Ziegler *et al* 2022). To assess potential for UK seafood to contribute to improving suboptimal nutrient intakes in adults and children (Gibson and Sidnell 2014, Derbyshire 2018), we extracted nutrient content for iodine and four vitamins (A, B12, D, and folate; µg 100 g^{-1} of raw flesh) from food composition tables for the top 90% seafood products available in the UK (Widdowson n.d., Norwegian Food Safety Authority 2021). Nutrient density estimates for UK seafood were recalculated including these five nutrients (i.e. across ten nutrients in total), and thus exceeded nutrient density values of the global seafood analysis.

In addition to nutrients and health benefits, preference for affordable, quality seafood is a key driver of consumer behaviour in the UK (Seafish 2019a). Although less important than price, seafood ecolabels can also positively influence consumer preference across Western Europe (Zander and Feucht 2018, Menozzi *et al* 2020), and promote behaviour shifts towards more sustainable products (Jacobs *et al* 2018). To assess these factors in the context of carbon footprints and nutritional potential, we next examined the affordability and (consumer-labelled) sustainability of the 12 most-produced seafoods in the UK. Average price (GBP per kg) was extracted from market surveys conducted by Seafish (Watson 2021) and sustainability scores were extracted from the Marine Conservation Society's Good Fish Guide (Marine Conservation Society 2022). We note that seafood sustainability is 'imperfectly measurable' (Roheim *et al* 2018), and ecolabels may target different aspects of sustainability, from sustainable fishing levels and habitat damage to pollution, bycatch and endangered species. Here, we use The Good Fish Guide sustainability metric as a standardised rating scheme with particular relevance for UK consumers, that qualitatively compares environmental impacts of processes that are specific to both wild (e.g. overfishing) and farmed (e.g. disease) products. Capture fisheries sustainability was assessed by ranking stock status (catch limits, biomass level, IUCN status), management (existence of regulatory frameworks), and capture method (habitat impacts) (Marine Conservation Society 2018) for 94 stocks relevant to UK seafood supply. Aquaculture sustainability was assessed by scoring feed resource use (traceability, sourcing), environmental impacts (habitat, water quality, disease), fish welfare, and regulations and management (enforcement of standards and third-party certification) (Marine Conservation Society 2020) for 13 farm systems (Atlantic salmon = 9, Rainbow trout = 2, mussels = 2) relevant to UK seafood. To facilitate comparisons between these two methodologies, we rescaled all sustainability ratings between 0 (low) and 1 (high sustainability). For capture fisheries, we also extracted indicators of fishing pressure and biological status for stocks of UK interest. These metrics were extracted for 231 stock-year combinations of cod, herring, mackerel, haddock and Norway lobster over 1990-2019, and

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used to assess long-term trends in fishing pressure relative to maximum sustainable yield (F relative to F_{MSY}) and reproductive capacity (spawning stock biomass relative to B_{Lim}) (Lynam 2021).

Data Availability Statement

The data that support the findings of this study will be openly available at a online repository.

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Supplementary Material

Supplementary Figures
Table S1
Table S2

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References

Avdelas L, Avdic-Mravlje E, Borges Marques A C, Cano S, Capelle J J, Carvalho N, Cozzolino M, Dennis J, Ellis T, Fernández Polanco J M, Guillen J, Lasner T, Le Bihan V, Llorente I, Mol A, Nicheva S, Nielsen R, Oostenbrugge H, Villasante S, Visnic S, Zhelev K and Asche F 2021 The decline of mussel aquaculture in the European Union: causes, economic impacts and opportunities *Rev. Aquac.* **13** 91–118

Belton B and Thilsted S H 2014 Fisheries in transition: Food and nutrition security implications for the global South *Global Food Security* **3** 59–66

Béné C, Barange M, Subasinghe R, Pinstrup-Andersen P, Merino G, Hemre G-I and Williams M 2015 Feeding 9 billion by 2050 – Putting fish back on the menu *Food Security* **7** 261–74

Bernhardt J R and O'Connor M I 2021 Aquatic biodiversity enhances multiple nutritional benefits to humans *Proc. Natl. Acad. Sci. U. S. A.* **118** Online: https://www.pnas.org/content/118/15/e1917487118.abstract

Bianchi M, Hallström E, Parker R W R, Mifflin K, Tyedmers P and Ziegler F 2022 Assessing seafood nutritional diversity together with climate impacts informs more comprehensive dietary advice *Communications Earth & Environment* **3** 1–12

Bucher T, Collins C, Rollo M E, McCaffrey T A, De Vlieger N, Van der Bend D, Truby H and Perez-Cueto F J A 2016 Nudging consumers towards healthier choices: a systematic review of positional influences on food choice *Br. J. Nutr.* **115** 2252–63

Cappell H T &. 2020 *English Aquaculture Strategy* (Produced by Poseidon Aquatic Resources Management Ltd for the Seafish Industry Authority)

Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets *Science* **370** 705–8

Clark M, Springmann M, Rayner M, Scarborough P, Hill J, Tilman D, Macdiarmid J I, Fanzo J, Bandy L and Harrington R A 2022 Estimating the environmental impacts of 57,000 food products *Proc. Natl. Acad. Sci. U. S. A.* **119** e2120584119

Clune S, Crossin E and Verghese K 2017 Systematic review of greenhouse gas emissions for different fresh food categories *J. Clean. Prod.* **140** 766–83

Costello C, Cao L, Gelcich S, Cisneros-Mata M Á, Free C M, Froehlich H E, Golden C D, Ishimura G, Maier J, Macadam-Somer I, Mangin T, Melnychuk M C, Miyahara M, de Moor C L, Naylor R, Nøstbakken L, Ojea E, O'Reilly E, Parma A M, Plantinga A J, Thilsted S H and Lubchenco J 2020 The future of food from the sea *Nature* 1–6

Costello C, Ovando D, Clavelle T, Strauss C K, Hilborn R, Melnychuk M C, Branch T A, Gaines S D, Szuwalski C S, Cabral R B, Rader D N and Leland A 2016 Global fishery prospects under contrasting management regimes *Proc. Natl. Acad. Sci. U. S. A.* **113** 5125–9

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F N and Leip A 2021 Food systems are responsible for a third of global anthropogenic GHG emissions *Nature Food* **2** 198–209

Department for Environment, Food and Rural Affairs 2022 Food statistics pocketbook Accessed 04/11/2022. https://www.gov.uk/government/statistics/food-statistics-pocketbook

Derbyshire E 2018 Micronutrient Intakes of British Adults Across Mid-Life: A Secondary Analysis of the UK National Diet and Nutrition Survey *Front Nutr* **5** 55

Drewnowski A, Rehm C D, Martin A, Verger E O, Voinnesson M and Imbert P 2015 Energy and nutrient density of foods in relation to their carbon footprint *Am. J. Clin. Nutr.* **101** 184–91

FAO 1989 FAO Yearbook - Yearbook of fishery statistics: *Catches and landings*

FAO 2016 FAO/INFOODS Food Composition Databases for Biodiversity v.3.0

FAO/WHO Expert Consultation on Human Vitamin and Mineral Requirements 2004 *Vitamin and Mineral Requirements in Human Nutrition* (FAO/WHO)

Franklin A 1997 An unpopular food? The distaste for fish and the decline of fish consumption in Britain *Food and Foodways* **7** 227–64

Froese R and Pauly D 2022 FishBase. Fish Nutrients Tool.

Garrett A and Caveen A 2018 *UK seafood supply base to 2030: An initial review of developments, implications and practical responses from industry and Seafish* (Seafish)

Gephart J A, Henriksson P J G, Parker R W R, Shepon A, Gorospe K D, Bergman K, Eshel G, Golden C D, Halpern B S, Hornborg S, Jonell M, Metian M, Mifflin K, Newton R, Tyedmers P, Zhang W, Ziegler F and Troell M 2021 Environmental performance of blue foods *Nature* **597** 360–5

Gephart J A and Pace M L 2015 Structure and evolution of the global seafood trade network *Environ. Res. Lett.* **10** 125014

Gibson S and Sidnell A 2014 Nutrient adequacy and imbalance among young children aged 1-3 years in the UK *Nutr. Bull.* **39** 172–80

Golden C D, Koehn J Z, Shepon A, Passarelli S, Free C M, Viana D F, Matthey H, Eurich J G, Gephart J A, Fluet-Chouinard E, Nyboer E A, Lynch A J, Kjellevold M, Bromage S, Charlebois P, Barange M, Vannuccini S, Cao L, Kleisner K M, Rimm E B, Danaei G, DeSisto C, Kelahan H, Fiorella K J, Little D C, Allison E H, Fanzo J and Thilsted S H 2021 Aquatic foods to nourish nations *Nature* **598** 315–20

Gutiérrez N L, Valencia S R, Branch T A, Agnew D J, Baum J K, Bianchi P L, Cornejo-Donoso J, Costello C, Defeo O, Essington T E, Hilborn R, Hoggarth D D, Larsen A E, Ninnes C, Sainsbury K, Selden R L, Sistla S, Smith A D M, Stern-Pirlot A, Teck S J, Thorson J T and Williams N E 2012 Eco-label conveys reliable information on fish stock health to seafood consumers *PLoS One*

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7 e43765

Haddad L, Hawkes C, Webb P, Thomas S, Beddington J, Waage J and Flynn D 2016 A new global research agenda for food *Nature* **540** 30–2

Hallström E, Bergman K, Mifflin K and Parker R 2019 Combined climate and nutritional performance of seafoods *J. Clean. Prod.* Online: https://www.sciencedirect.com/science/article/pii/S0959652619313162

Halpern B S, Frazier M, Verstaen J, Rayner P-E, Clawson G, Blanchard J L, Cottrell R S, Froehlich H E, Gephart J A, Jacobsen N S, Kuempel C D, McIntyre P B, Metian M, Moran D, Nash K L, Többen J and Williams D R 2022 The environmental footprint of global food production *Nature Sustainability* 1–13

Headey D D and Alderman H H 2019 The Relative Caloric Prices of Healthy and Unhealthy Foods Differ Systematically across Income Levels and Continents *J. Nutr.* **149** 2020–33

Headey D, Hirvonen K and Hoddinott J 2018 Animal Sourced Foods and Child Stunting *Am. J. Agric. Econ.* **100** 1302–19

Hicks C C, Cohen P J, Graham N A J, Nash K L, Allison E H, D'Lima C, Mills D J, Roscher M, Thilsted S H, Thorne-Lyman A L and MacNeil M A 2019 Harnessing global fisheries to tackle micronutrient deficiencies *Nature* **574** 95–8

Hicks C C, Graham N A J, Maire E and Robinson J P W 2021 Secure local aquatic food systems in the face of declining coral reefs *One Earth* **4** 1214–6

Hilborn R, Banobi J, Hall S J, Pucylowski T and Walsworth T E 2018 The environmental cost of animal source foods *Front. Ecol. Environ.* **16** 329–35

Honkanen P and Young J A 2015 What determines British consumers' motivation to buy sustainable seafood? *British Food Journal* **117** 1289–302

Hornborg S and Smith A D M 2020 Fisheries for the future: greenhouse gas emission consequences of different fishery reference points *ICES J. Mar. Sci.* **77** 1666–71

Jacobs S, Sioen I, Marques A and Verbeke W 2018 Consumer response to health and environmental sustainability information regarding seafood consumption *Environ. Res.* **161** 492–504

Jennings S, Stentiford G D, Leocadio A M, Jeffery K R, Metcalfe J D, Katsiadaki I, Auchterlonie N A, Mangi S C, Pinnegar J K, Ellis T, Peeler E J, Luisetti T, Baker-Austin C, Brown M, Catchpole T L, Clyne F J, Dye S R, Edmonds N J, Hyder K, Lee J, Lees D N, Morgan O C, O'Brien C M, Oidtmann B, Posen P E, Santos A R, Taylor N G H, Turner A D, Townhill B L and Verner-Jeffreys D W 2016 Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment *Fish Fish* **17** 893–938

Koehn J Z, Allison E H, Golden C D and Hilborn R 2022 The role of seafood in sustainable diets *Environ. Res. Lett.* Online: http://dx.doi.org/10.1088/1748-9326/ac3954

Kovacs B, Miller L, Heller M C and Rose D 2021 The carbon footprint of dietary guidelines around the world: a seven country modeling study *Nutr. J.* **20** 15

Lynam C, Bluemel J, Ribeiro J, Garnacho E and Angelus S 2021 *International (ICES) and national (UK) fish stock and shellfish stock data from 2020 assessment year* (CEFAS) Online: http://dx.doi.org/10.14466/CefasDataHub.120

MacLeod M J, Hasan M R, Robb D H F and Mamun-Ur-Rashid M 2020 Quantifying greenhouse gas

Deleted:

emissions from global aquaculture *Sci. Rep.* **10** 11679

Madin E M P and Macreadie P I 2015 Incorporating carbon footprints into seafood sustainability certification and eco-labels *Mar. Policy* **57** 178–81

Marine Conservation Society 2018 *Wild Capture Ratings Methodology*

Marine Conservation Society 2020 *Aquaculture Ratings Methodology Handbook*

Marine Conservation Society 2022 *Good Fish Guide*. Accessed 09-11-2022.

Melnychuk M C, Kurota H, Mace P M, Pons M, Minto C, Osio G C, Jensen O P, de Moor C L, Parma A M, Richard Little L, Hively D, Ashbrook C E, Baker N, Amoroso R O, Branch T A, Anderson C M, Szuwalski C S, Baum J K, McClanahan T R, Ye Y, Ligas A, Bensbai J, Thompson G G, DeVore J, Magnusson A, Bogstad B, Wort E, Rice J and Hilborn R 2021 Identifying management actions that promote sustainable fisheries *Nature Sustainability* Online: https://doi.org/10.1038/s41893-020-00668-1

Menozzi D, Nguyen T T, Sogari G, Taskov D, Lucas S, Castro-Rial J L S and Mora C 2020 Consumers' Preferences and Willingness to Pay for Fish Products with Health and Environmental Labels: Evidence from Five European Countries *Nutrients* **12** Online: http://dx.doi.org/10.3390/nu12092650

Miller V, Reedy J, Cudhea F, Zhang J, Shi P, Erndt-Marino J, Coates J, Micha R, Webb P, Mozaffarian D, Abbott P, Abdollahi M, Abedi P, Abumweis S, Adair L, Al Nsour M, Al-Daghri N, Al-Hamad N, Al-Hooti S, Al-Zenki S, Alam I, Ali J H, Alissa E, Anderson S, Anzid K, Arambepola C, Arici M, Arsenault J, Asciak R, Barbieri H E, Barengo N, Barquera S, Bas M, Becker W, Beer-Borst S, Bergman P, Biró L, Boindala S, Bovet P, Bradshaw D, Bukhary N B I, Bundhamcharoen K, Caballero M, Calleja N, Cao X, Capanzana M, Carmikle J, Castetbon K, Castro M, Cerdena C, Chang H-Y, Charlton K, Chen Y, Chen M F, Chiplonkar S, Cho Y, Chuah K-A, Costanzo S, Cowan M, Damasceno A, Dastgiri S, De Henauw S, DeRidder K, Ding E, Dommarco R, Don R, Duante C, Duleva V, Duran Aguero S, Ekbote V, El Ati J, El Hamdouchi A, El-kour T, Eldridge A, Elmadfa I, Esteghamati A, Etemad Z, Fadzil F, Farzadfar F, Fernandez A, Fernando D, Fisberg R, Forsyth S, Gamboa-Delgado E, Garriguet D, Gaspoz J-M, Gauci D, Geleijnse M, Ginnela B, Grosso G, Guessous I, Gulliford M, Gunnarsdottir I, Hadden W, Hadziomeragic A, Haerpfer C, Hakeem R, Haque A, et al 2022 Global, regional, and national consumption of animal-source foods between 1990 and 2018: findings from the Global Dietary Database *The Lancet Planetary Health* **6** e243–56

Nash K L, MacNeil M A, Blanchard J L, Cohen P J, Farmery A K, Graham N A J, Thorne-Lyman A L, Watson R A and Hicks C C 2022 Trade and foreign fishing mediate global marine nutrient supply *Proc. Natl. Acad. Sci. U. S. A.* **119** e2120817119

Naylor R L, Kishore A, Sumaila U R, Issifu I, Hunter B P, Belton B, Bush S R, Cao L, Gelcich S, Gephart J A, Golden C D, Jonell M, Koehn J Z, Little D C, Thilsted S H, Tigchelaar M and Crona B 2021 Blue food demand across geographic and temporal scales *Nat. Commun.* **12** 5413

Norwegian Food Safety Authority 2021 Norwegian Food Composition Database Online: www.matvaretabellen.no

Nøstbakken O J, Rasinger J D, Hannisdal R, Sanden M, Frøyland L, Duinker A, Frantzen S, Dahl L M, Lundebye A-K and Madsen L 2021 Levels of omega 3 fatty acids, vitamin D, dioxins and dioxin-like PCBs in oily fish; a new perspective on the reporting of nutrient and contaminant data for risk-benefit assessments of oily seafood *Environ. Int.* **147** 106322

Parker R W R, Blanchard J L, Gardner C, Green B S, Hartmann K, Tyedmers P H and Watson R A 2018 Fuel use and greenhouse gas emissions of world fisheries *Nat. Clim. Chang.* **8** 333–7

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Parker R W R and Tyedmers P H 2015 Fuel consumption of global fishing fleets: current understanding and knowledge gaps *Fish Fish* **16** 684–96

Parodi A, Leip A, De Boer I J M, Slegers P M, Ziegler F, Temme E H M, Herrero M, Tuomisto H, Valin H, Van Middelaar C E, Van Loon J J A and Van Zanten H H E 2018 The potential of future foods for sustainable and healthy diets *Nat Sustain* **1** 782–9

Rittenschober D, Stadlmayr B, Nowak V, Du J and Charrondiere U R 2016 Report on the development of the FAO/INFOODS user database for fish and shellfish (uFiSh) – Challenges and possible solutions *Food Chem.* **193** 112–20

Robinson J P W, Nash K L, Blanchard J L, Jacobsen N S, Maire E, Graham N A J, MacNeil M A, Zamborain-Mason J, Allison E H and Hicks C C 2022 Managing fisheries for maximum nutrient yield *Fish Fish* Online: https://onlinelibrary.wiley.com/doi/10.1111/faf.12649

Rockström J, Edenhofer O, Gaertner J and DeClerck F 2020 Planet-proofing the global food system *Nature Food* **1** 3–5

Roheim C A, Bush S R, Asche F, Sanchirico J N and Uchida H 2018 Evolution and future of the sustainable seafood market *Nature Sustainability* **1** 392–8

Seafish 2019a Exploring shopper behaviour when purchasing fresh fish and seafood: Category benchmark report *IGD ShopperVista*

Seafish 2019b *Market Insight Factsheet: Seafood Consumption*

Seafood Watch. Seafood Carbon Emissions Tool *http://seafoodco2.dal.ca/* Online: http://seafoodco2.dal.ca/

Springmann M, Clark M A, Rayner M, Scarborough P and Webb P 2021 The global and regional costs of healthy and sustainable dietary patterns: a modelling study *Lancet Planet Health* **5** e797–807

Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky B L, Lassaletta L, de Vries W, Vermeulen S J, Herrero M, Carlson K M, Jonell M, Troell M, DeClerck F, Gordon L J, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray H C J, Tilman D, Rockström J and Willett W 2018 Options for keeping the food system within environmental limits *Nature* **562** 519–25

Stevens G A, Beal T, Mbuya M N N, Luo H, Neufeld L M and Global Micronutrient Deficiencies Research Group 2022 Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: a pooled analysis of individual-level data from population-representative surveys *Lancet Global Health* **10** e1590–9

Thilsted S H, Thorne-Lyman A, Webb P, Bogard J R, Subasinghe R, Phillips M J and Allison E H 2016 Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era *Food Policy* **61** 126–31

Tilman D and Clark M 2014 Global diets link environmental sustainability and human health *Nature* **515** 518–22

Tuomisto J T, Asikainen A, Meriläinen P and Haapasaari P 2020 Health effects of nutrients and environmental pollutants in Baltic herring and salmon: A quantitative benefit-risk assessment *BMC Public Health* **20** Online: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85077941023&doi=10.1186%2fs12889-019-8094-1&partnerID=40&md5=be4ac940955cebdd9c7ac23ed9cf2a27

Watson 2022 *Seafood Consumption (2022 Update)* (Seafish)

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Watson 2021 *Seafood in multiple retail (2021 update)* (Seafish)

Widdowson M A Composition of foods integrated dataset (CoFID) Online: https://www.gov.uk/government/publications/composition-of-foods-integrated-dataset-cofid

Willer D F and Aldridge D C 2019 Microencapsulated diets to improve bivalve shellfish aquaculture for global food security *Global Food Security* **23** 64–73

Willer D F, Robinson J P W, Patterson G T and Luyckx K 2022 Maximising sustainable nutrient production from coupled fisheries-aquaculture systems *PLOS Sustainability and Transformation* **1** e0000005

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon L J, Fanzo J, Hawkes C, Zurayk R, Rivera J A, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell S E, Srinath Reddy K, Narain S, Nishtar S and Murray C J L 2019 Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems *Lancet* **393** 447–92

Xu X, Sharma P, Shu S, Lin T-S, Ciais P, Tubiello F N, Smith P, Campbell N and Jain A K 2021 Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods *Nature Food* **2** 724–32

Zander K and Feucht Y 2018 Consumers' willingness to pay for sustainable seafood made in Europe *J. int. food agribus. mark.* **30** 251–75

Ziegler F, Hornborg S, Green B S, Eigaard O R, Farmery A K, Hammar L, Hartmann K, Molander S, Parker R W R, Skontorp Hognes E, Vázquez-Rowe I and Smith A D M 2016 Expanding the concept of sustainable seafood using Life Cycle Assessment *Fish Fish* **17** 1073–93

Ziegler F, Tyedmers P H and Parker R W R 2022 Methods matter: Improved practices for environmental evaluation of dietary patterns *Glob. Environ. Change* **73** 102482

Ziegler F, Winther U, Hognes E S, Emanuelsson A, Sund V and Ellingsen H 2013 The carbon footprint of Norwegian seafood products on the global seafood market: Carbon footprint of Norwegian seafood on global market *J. Ind. Ecol.* **17** 103–16