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## Environmental burden of fish in healthy and sustainable diets

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### ABSTRACT

Fish is widely promoted as part of healthy dietary patterns. The aim of this review was to summarise current literature on the environmental footprint of fish and its role within sustainable diets. Fish generally represents a minor share of total dietary environmental impacts, contributing to a smaller proportion of greenhouse-gas emissions (GHGe), land and water use than meat and other animal products. Several modelling studies showed that substituting meat with fish or increasing fish intake within optimised dietary patterns can reduce environmental impacts, although the magnitude varies by country, diet type, and fish species. However, some analyses reported increased GHGe associated with higher fish intake, especially in models ensuring nutritional quality. Overall, fish consumption is compatible with achieving nutritionally adequate and lower environmental impacts, although optimal match between environmental boundaries and nutritional needs is not always possible. These findings suggest that fish can play a constructive role in sustainable diets when integrated thoughtfully within broader dietary shifts.

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## Introduction

Food systems are increasingly recognised as a major driver of global environmental change (Gomes et al. 2024). Current dietary patterns are responsible for a substantial share of anthropogenic greenhouse gas emissions (GHGe), land degradation, freshwater use, and biodiversity loss (Alves et al. 2024; Mandouri et al. 2025). Estimates consistently indicate that the food system contributes approximately 30% of global GHGe (Madin and Macreadie 2015), uses over 40% of habitable land (Ramankutty et al. 2018), and accounts for 70% of freshwater withdrawals (Ringler et al. 2022), leading to important biodiversity loss (Boakes et al. 2024). As population growth, urbanisation and shifts towards resource-intensive diets continue, transitioning towards sustainable dietary patterns has become a central strategy in climate mitigation frameworks (Springmann et al. 2018a). Sustainable diets are defined as those that achieve nutrient adequacy and promote long-term health while minimising environmental impacts and remaining

culturally acceptable and economically accessible (Grosso et al. 2020b). Such an approach has been hypothesised not only to maintain planetary health but also to ensure food security globally (Mora et al. 2020).

Within this context, the role of animal-source foods has been the focus of intensive examination, given their disproportionate environmental footprint relative to plant-based foods (Godfray et al. 2018; Bidoglio et al. 2024). However, not all animal-source foods exert equal environmental pressures. In particular, a “pescaarian” dietary pattern including fish and seafood may occupy a distinctive position providing a significant reduction in overall mortality risk while often exerting lower GHGe and land use impacts than conventional diets (Springmann et al. 2018b). In fact, fish is most ubiquitously included, though at varying recommended levels, within many national food-based dietary guidelines and dietary recommendations from scientific societies (Herforth et al. 2019). However, according to a recent overview on current dietary intakes and optimised diets for reduced environmental impacts, fish consumption is

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globally low and relatively poorly represented in current diets, especially in relation to recommended intakes or optimised models (Kalmouropoultidou et al. 2025).

From a health perspective, regular fish consumption is associated with reduced cardiovascular risk and lower all-cause mortality (Jurek et al. 2022), reduced risk of certain cancers (Lee et al. 2020), and beneficial effects against neurocognitive decline (Godos et al. 2024). Observational and clinical evidence supports the protective role of fish mediated by a complex food matrix composed by high-quality protein, long-chain n-3 fatty acids (particularly EPA and DHA), and essential micro-nutrients (such as, iodine, selenium, and vitamin D, among others) (Khalili Tilami and Sampels 2017; Noreen et al. 2025). Nonetheless, balancing these health benefits with the environmental performance of fisheries and aquaculture is complex. The environmental footprint of seafood varies substantially across species, production systems, and supply chains, ranging from low-impact pelagic fish and mollusks to carbon-intensive crustaceans and certain aquaculture operations (Halpern et al. 2022). Consequently, the sustainability of increasing fish consumption depends not only on total intake but also on species substitution patterns, transportation, refrigeration, and energy input for aquaculture (including mariculture) products (Madin and Macreadie 2015).

Given these nuances, scientific debate persists regarding the role of fish within diets optimised for both health and environmental outcomes. Lack of clarity on this matter underscores the need to synthesise the broad and heterogeneous evidence on how fish contributes to environmental footprints and how fish intake is modified in diets optimised for health, environmental impact, or both. The present review provides a comprehensive and critical synthesis of findings from modelling studies, environmental footprint assessments, and dietary scenario analyses. Specifically, we summarised (i) the environmental contribution of fish in current dietary patterns; (ii) how fish intake changes when diets are optimised for nutritional quality and/or environmental sustainability; and (iii) what would be the contribution of fish in modelled healthy and sustainable dietary patterns. Through this synthesis, we aim to clarify the role of fish within healthy and sustainable diets and to provide evidence-based insights for policymakers and researchers seeking to align dietary guidelines with planetary health goals.

## Literature review methodology

This work was conducted as a narrative, non-systematic review aimed at synthesising the available evidence

on the environmental impact of fish within dietary patterns. Relevant literature was identified through targeted searches of the scientific literature, focusing on studies assessing environmental footprints of diets, dietary optimisation models, and observational analyses of food consumption patterns. Priority was given to studies reporting quantitative estimates of environmental indicators (e.g. greenhouse gas emissions, land use, water use) and those examining the role of fish within current or modelled dietary scenarios. Given the heterogeneity of the field, no formal systematic search strategy, predefined inclusion/exclusion criteria, or risk-of-bias assessment was applied. Instead, studies were selected based on their relevance to the research objectives, methodological rigour, and ability to contribute to a comprehensive overview across different geographic contexts and analytical approaches. As a result, the included evidence reflects a broad but non-exhaustive synthesis of the literature, consistent with the exploratory and integrative nature of this review.

## Environmental impact of fish in current diets

Understanding the environmental implications of fish consumption within observed dietary patterns requires integrating findings across multiple cohorts, geographic contexts, and methodological approaches.

Early evidence from the EPIC-Oxford cohort illustrated the substantially lower GHGe associated with diets that include fish instead of meat. Among more than 65,000 UK adults, fish-eaters exhibited markedly lower emissions compared with meat-eaters: GHGe averaged 3.91 kg CO<sub>2eq</sub>/2000 kcal, compared with 7.19, 5.63, and 4.67 kg CO<sub>2eq</sub>/2000 kcal in high-, medium-, and low-meat eaters, respectively. Emissions among meat-eaters were 46% higher in women and 51% higher in men relative to fish eaters, emphasising the disproportionate environmental burden of meat-based diets relative to those incorporating more fish (Scarborough et al. 2014). More recent nationally representative UK data from the UK National Diet and Nutrition Survey (NDNS) 2008–09 and 2013–14 ( $n=3502$ , age >19 y) reinforced the finding that fish contributes a modest proportion of dietary GHGe: with an average intake of 30 g/day, fish accounted for roughly 6% of total dietary GHGe (substantially lower than contributions from meat or dairy) (Murakami and Livingstone 2018). Further UK data from the myfood24 study (a validation cohort involving 212 participants, 18–65 y) tried to calculate the impact of 3000 food consumption on GHG emissions and

connection to individual environmental impact showed that, while average diet-related GHGe were 7.4 kg CO<sub>2eq</sub>/day, meat accounted for the largest share (32%), with fish contributing far less, reinforcing the consistent conclusion across datasets that fish is a relatively minor contributor to total diet-related emissions when compared to meat (Rippin et al. 2021). A Dutch study from a representative sample of the NQplus study ( $n=1169$ , 20–70 y) using both FFQ and 24-h recall data arrived at similar conclusions: fish intake, averaging 0.7 g/day, contributed consistently low proportions to GHGe, fossil energy use, land use, and pReCiPe scores (a method calculating a score based on combination of the characterisation, normalisation, and weighing factors of these three indicators), reinforcing its modest contribution to environmental pressures relative to other foods (Mertens et al. 2019a). Also in the Netherlands, participants belonging to the EPIC-NL cohort ( $n=36209$ , 20–70 y) were evaluated using a 178-item FFQ and an ad hoc LCA estimation to investigate the environmental impact (in terms of GHGe) of derived dietary patterns: higher adherence to a “plant-based patterns” was characterised by consumption of 14 g/d of fish, an overall lower environmental impact, and a better nutritional quality, as compared to other derived patterns (Biesbroek et al. 2018). In a study from the same cohort ( $n=8932$ , 18–65 y) describing GHGe associated with dietary changes over 20 years, fish consumption increased from baseline to follow-up in both men and women (in men, intake rose from 4.2 to 13.6 g/1000 kcal, while in women it increased from 5.8 to 16.8 g/1000 kcal) and subsequently fish-related GHGe also increased, from 0.04 to 0.13 kgCO<sub>2eq</sub>/1000 kcal in men and from 0.05 to 0.16 kgCO<sub>2eq</sub>/1000 kcal in women (Biesbroek et al. 2019). In France, data from a representative sample of participants enrolled in the NutriNet-Santé cohort ( $n=34193$ , mean age 53.3 y) were analysed to describe observed diets across different levels of diet-related GHGe. Dietary intake was assessed using a 264-item organic semi-quantitative FFQ (Org-FFQ), while the environmental impact of diets was estimated through the DIALECTE tool: individuals following a medium-impact diet (Q3, 1229–1589 kgCO<sub>2eq</sub>/year) reported the highest fish consumption (52.6 g/day), compared with those adhering to a low-impact diet (Q1, 347–816 kgCO<sub>2eq</sub>/year; 36.6 g/day) and a high-impact diet (Q5, 2318–4099 kgCO<sub>2eq</sub>/year; 48.5 g/day), with fish contributing approximately 4% of total diet-related GHGe in the lowest-impact quintile and about 1–2% in the highest-impact quintile (Q5) (Seconda et al. 2018). Additional findings from Southern Europe reinforce the generally modest

environmental footprint of fish. In the Spanish SUN cohort, a dynamic Spanish cohort composed of university graduates ( $n=17387$ ; mean age 37 y), fish and seafood consumption increased across quartiles of GHGe, energy use, and water use, though it decreased across land-use quartiles, indicating a variable environmental profile depending on the outcome considered (Fresán et al. 2020). In Southern Italy, individuals from a local survey ( $n=2044$ , >18 y) with the highest sustainability scores had substantially greater fish consumption (85 g/day) assessed through a 110-item FFQ; moreover, fish contributed modest proportions to environmental impacts (such as approximately 7% of GHGe, 15% of energy use, 2–3% of water use, and <2% of land use) confirming its comparatively favourable profile within Mediterranean-type diets (Grosso et al. 2020a).

However, nuance is provided by Dutch analyses linking sustainability and health metrics. In the NQplus cohort testing for GHG emissions, land use, and fossil energy use as environmental outputs, fish consumption was significantly higher in dietary profiles characterised by high health scores but low sustainability scores ( $32 \pm 53$  g/day) and lowest in diets with the opposite pattern ( $5 \pm 16$  g/day) (van Bussel et al. 2019). Meanwhile, the Dutch National Food Consumption Survey (DNFCS) 2012–2016 ( $n=4313$ , 1–79 y) revealed that although fish (assessed with two non-consecutive 24-h recalls and ad hoc LCA estimation to evaluate impact of current food consumption on various environmental outputs) contributed only 0.13 kg CO<sub>2eq</sub>/day and 0.001 m<sup>3</sup> of blue water use, a higher fish ratio within diets was still significantly associated with increased GHGe and blue water use in fully adjusted models ( $\beta=0.002$  and  $\beta=0.002$ , respectively), suggesting that even relatively low levels of fish intake can measurably affect environmental indicators when assessed across dietary components (Vellinga et al. 2019). Notably, another report from the same data source underlined that under any possible scenario modelled to identify a dietary pattern optimised for vitamin D intake, fish consumption needed to be increased while inevitably affecting the related carbon footprint (Bruins and Létinois 2021). Moreover, a cross-national comparison involving cohorts from Denmark, the Czech Republic, Italy, and France belonging to National Survey on Diet and Physical Activity 2005–2008 ( $n=1739$ ), SISP04 2003–2004 ( $n=1666$ ), INRAN-SCAI 2005–2006 ( $n=2313$ ), INCA-2 study 2006–2007 ( $n=2276$ ), respectively, using different methods (such as, 7-d diet record on consecutive days, 24-h recall spaced over three-to-five months, 3-d diet record on consecutive days) for

dietary assessment and a SHARP-ID database to assess environmental impact, found that, although fish accounted for a relatively small proportion of GHGe and land use across countries, its environmental impact increased with higher consumption: specifically, a 4% increase in energy intake from fish (~60 g/day) was associated with a 7% increase in GHGe, while land use increased only minimally (+2%) (Mertens et al. 2019b). Recent evidence from the Epidemiologic Health Investigation of Teenagers (EPI-Teens) cohort in Portugal adds another counterpoint. In this sample of 1554 participants, fish and seafood represented the second highest contributor to GHGe (29.2%), although their contributions to other environmental outcomes were negligible relative to other animal-source foods, which accounted collectively for up to 80% of impacts depending on the specific outcome. These findings showed that although fish is generally lower impact than meat, increasing fish consumption is not environmentally neutral, especially depending on the species consumed (Álvarez-Álvarez et al. 2024).

Similar patterns emerged outside Europe. For instance, in Lebanon, an analysis of a representative sample from the Nutrition and Non-Communicable Disease Risk Factor Survey 2008–2009 ( $n=337$ , >18y) using a 61-item FFQ and LCA analyses to assess dietary intakes and environmental footprint analyses, identified fish primarily within a “High Protein” dietary pattern: although this pattern included substantial fish intake, absolute impacts varied widely (such as, GHGe of  $6.86 \pm 11.06$  kg CO<sub>2eq</sub>/day, water use of  $3.22 \pm 7.76$  L/day, and energy use of  $19.50 \pm 17.89$  MJ/day) (Naja et al. 2018). Evidence from the United States National Health and Nutrition Examination Survey (NHANES) 2005–2010 ( $n=16,800$  aged  $\geq 18$  y) showed that higher GHGe diets contained significantly more seafood compared with lowest-GHGe diets ( $0.41 \pm 0.03$  oz eq/1000 kcal and  $0.21 \pm 0.01$  oz eq/1000 kcal, respectively). However, higher diet quality measured by the healthy eating index (HEI) “Seafood and plant proteins” component, was associated with lower GHGe diets – higher in Low-GHGe diets compared to High-GHGe diets (HEI score:  $2.38 \pm 0.06$  vs.  $1.60 \pm 0.06$ ) – suggesting that in the US, seafood appears in both higher- and lower-impact dietary profiles depending on overall dietary patterns (Rose et al. 2019). In Japan data from 392 adults, aged 20–69 y, were analysed to examine the relationship between diet-related GHGe and the prevalence of inadequate nutrient intake using four non-consecutive-day diet records, while environmental impacts estimated through a database based on the

Global Link Input-Output (GLIO) model: fish and seafood consumption increased progressively across GHGe quartiles, from 31 g/day in the lowest quartile to 47 g/day in the highest quartile; at the same time, total diet-related GHGe also rose from the lowest to the highest quartile, indicating that higher fish and seafood consumption was associated with diets characterised by greater overall GHGe (Sugimoto et al. 2020). A study in Canada, including participants from a nationally representative sample of adults from Canadian Community Health Survey (CCHS) ( $n=13612$ , aged  $\geq 19$  y) was conducted in order to describe the carbon footprint of self-selected Canadian diets with dietary intake assessed using a 24-h recall, while environmental impact was assessed using a database of Food Impacts on the Environment for Linking to Diets (dataFIELD): fish and shellfish contributed about 5% of the total dietary GHGe, compared to other food groups; in particular shellfish intake was greater for high compared to low-GHGe diet consumers (about +5.6 g/1000 kcal) (Auclair and Burgos 2021).

Taken together, the literature reveals a nuanced picture. Across most populations, fish contributes a relatively small proportion of overall dietary environmental burdens, particularly when compared with ruminant meat. However, the magnitude of its impact is context-dependent, primarily influenced by its overall intake, but also species choice, dietary patterns, and the distribution of environmental impacts across GHGe, land use, water use, and energy use. While fish can significantly lower dietary GHGe when substituted for meat, increased fish intake does not universally guarantee environmental benefits nor being consistently included in low-environmental footprint diets, highlighting the need for context-specific assessments. These patterns set the stage for examining how fish consumption behaves in optimised dietary models aiming simultaneously for nutritional adequacy and environmental sustainability.

### **Fish consumption in optimized healthy and sustainable diets**

Modelling studies aiming to design nutritionally adequate and environmentally sustainable diets consistently show that fish occupies a central role within most optimised dietary patterns. Although fish is often increased in nutritional optimisation scenarios due to its high nutrient density, especially its provision of long-chain omega-3 fatty acids, optimised models may impose environmental constraints that interact with these nutritional requirements in complex ways. As a result, optimised diets might involve substantial shifts

in fish consumption, but the direction and magnitude of these changes differ considerably depending on model assumptions, environmental targets, cultural dietary baselines, and the basket of fish species considered.

Across diverse regions, a recurrent finding is that optimised diets designed primarily for nutritional adequacy tend to require higher fish consumption compared with observed diets. Early efforts to quantify the environmental burden of fish within whole diets came from large European cohorts. In the Netherlands, analysis of the EPIC-NL ( $n=40,011$ ), PROSPECT ( $n=17,357$  F, 49–70 y) and MORGEN ( $n=22,654$  MF, 20–59 y) studies showed that habitual fish consumption was extremely low (approximately 0.4 g/day) contributing just 2.1% of total dietary  $\text{CO}_{2\text{eq}}$  and 0.8% of land use of total diet; nevertheless, modelling scenarios in which 35 g/day of meat were substituted with fish led to measurable environmental benefits, including a 4.5% reduction in GHGe and a 9.8% reduction in land use, alongside a 19% reduction in mortality risk (Biesbroek et al. 2014). Studies modelling Dutch adult diets from the DNFCS ( $n=699$ ; 31–50 y) indicated that moving from the habitual diet to a nutritionally adequate diet necessitated a marked increase in fish and shellfish intake from 18 g/day at baseline to 54 g/day in a GHGe-target scenario, reflecting a substantial nutrient deficiency of current dietary patterns and the high nutrient density of fish in meeting optimal EPA and DHA requirements as well as the plausibility of its sustainable inclusion (Broekema et al. 2020). More complex patterns have been observed in a multicentric study in 2020 from Denmark, Czech Republic, Italy and France, aiming to explore the nutritional and GHGe impacts of meat replacers from participants belonging to DANSDA ( $n=1385$ ), SISPO4 ( $n=1386$ ), INRAN-SCAI ( $n=1978$ ) and INCA-2 study ( $n=1713$ ) cohorts; an increase in fish consumption was observed in all dietary optimised patterns, but the impact of this increase differed across countries and also between the different types of optimised diets (Mertens et al. 2020). The results from the INCA-2 study were substantially mirroring those presented in an earlier study showing that GHGe from fish consumption tends to be higher in optimised diets with higher nutritional quality (Vieux et al. 2013). From the same survey ( $n=3075$ , >18 y), a more elaborated analysis using an LCA method to assess the impact of introducing nutrient bioavailability and co-production links considerations on the dietary changes needed to improve diet sustainability and to estimate GHGe, atmospheric acidification, marine eutrophication, showed that in most optimised

diet models in both genders, compared to the observed diet, a reduction in GHGe in g/ $\text{CO}_2$  equivalents was observed for the fish subgroup, while a reduction in eutrophication levels in g/Neq was observed for fish consumption only in women contrasting an increase observed in men, always starting from the observed diet (Barré et al. 2018). Additionally, a subgroup analysis referring to the years 2006–2007 ( $n=1678$ , 18–65 y) exploring the dietary changes needed in order to reach a nutritionally adequate diet with 10% lower GHGe, both scenarios with and without constraints, an increase in the plant:animal protein ratio was suggested, with an increase in oily fish consumption was observed in both men and women compared to the observed diet, accompanied by a reduction in GHGe in the protein adequate model (de Gavelle et al. 2020). Data from participants belonging to the 2013 Family Food Module of The Living Costs and Food Survey ( $n=5144$ ) in UK used to model diets that meet dietary requirements for health and reduce GHGe showed that in order to reach GHGe target of 1.78 kg  $\text{CO}_{2\text{eq}}$ /person per day, fish purchases had to increase from 16 and 19 g/day respectively from low income and high income in 2013 diet to 39 g/day in the optimised diet both low and high income (Reynolds et al. 2019).

Some studies investigated the differences between current diets and diets optimised for general national guidelines and the EAT-Lancet planetary health diet. In Sweden, a representative sample of Swedish adults from Swedish dietary survey Riksmaten Vuxna 2010–11 ( $n=1797$ , 18–80 y) was analysed along with their web-based 4-day diary and through climate database developed and maintained by the Research Institutes of Sweden (RISE) was calculated  $\text{CO}_{2\text{eq}}$  emission between EAT-Lancet diet and different versions of optimised diet elaborated using Swedish dietary data: every version of the optimised diet was higher in fish consumption as compared to the EAT-Lancet Diet (about 5% vs about 2% of daily estimated energy requirement) (Eustachio Colombo et al. 2024). Similarly, a study from Norway, analysed data from participants enrolled in the Norkost 3 survey (2010–2011), including 1787 adults aged 18–70 y, with dietary intake assessed using 24-h dietary recalls, while environmental impacts were estimated using GHGe and resource-use values derived from previously published LCA analyses showed that fish and shellfish accounted for about 2–3% of total daily energy intake and contributed about 3–4% to global warming potential, 3–4% to freshwater eutrophication, 5–7% to marine eutrophication and 3–4% to terrestrial acidification and a lower contribution for resource-use indicators,

representing around 2–3% of total WU and 1–2% of land use; nonetheless, diets optimised based on Norwegian dietary guidelines and the EAT-Lancet diet led to reduction from 78 g/10 MJ to 70 g/10 MJ and 27 g/10 MJ, respectively (Lengle et al. 2024). Similar findings have been reported using data from the NutriNet-Santé cohort in France, considering environmental indicators such as GHGe, cumulative energy demand, and land occupation showing that consumption of fish was within the target values of the EAT-Lancet diet while the final optimised model estimated significant increases in fish consumption among all observed starting diet types (Kesse-Guyot et al. 2022).

The observed increase in fish consumption is generally needed to compensate for the reduction of intake of more environmentally impacting food groups. For instance, one study from nationally cross-sectional survey as part of the Transition and Health Impact in North Africa (TAHINA) project ( $n=7209$ , 35–70 y) noted that while the total quantity of “meat–fish–eggs” group assessed by a 138-item FFQ remained unchanged, the internal distribution shifted towards fish by approximately 15%, indicating a compensatory reduction in meat intake when the dual goals of nutritional adequacy and reduced environmental impact were prioritised (Perignon et al. 2019). Similarly, a study using data from a nationally representative sample of French adults ( $n=1899$ , >18 y), with dietary intake assessed using 7-day food records, and environmental impacts estimated through a hybrid input-output LCA method showed that in the scenario with constraints on all nutrients (ADEQ scenario), reductions in GHGe were primarily achieved through decreases in ruminant and deli meat consumption, while fish intake was preserved or increased; within the Meat/Fish/Eggs food group, fish effectively replaced ruminants and deli meats, contribution to a 30% reduction in GHGe, maintaining total Meat/Fish/Egg intake at approximately 100 g/day, and supporting an increase in fruit and vegetable consumption (Perignon et al. 2016). Also, optimisation studies that incorporate both health and environmental objectives often show not only an increase in total fish consumption but also intra-group substitutions. For instance, evidence from Danish National Survey of Diet and Physical activity (DANSDA) ( $n=2492$ ) and their 7-day pre-coded food diary to derive a nutritionally adequate and healthy diet that has the least deviation possible from the average observed diet of Danish adults while aiming for a GHGe reduction of 30% offers a parallel example: in the nutritional and environmental optimised diet, total fish and shellfish

intake increased by 28% (from the reported 36 g/d to 46 g/d), accompanied by a deliberate shift towards lower-GHGe fatty fish species (Nordman et al. 2023). Data from the national representative cross-sectional survey of adults of the National Diet and Nutrition Survey 2008–11 ( $n=1491$ ) in the UK used to model sustainable and healthy dietary recommendations with 25% GHGe reduction showed that fish was one of the most commonly added foods in the diet: to achieve optimal intake of white fish and oily fish for sustainable and healthy diets targets, it was necessary to add about 10 g/d of white fish and 25 g/d of oily fish (Horgan et al. 2016). Such findings emphasise that species-specific environmental performance may steer optimisation outcomes.

Some studies exploring the optimisation of current diets towards more sustainable dietary patterns differentiating between sex emphasised substantial differences between actual dietary patterns between men and women. A multi-national analysis from Finland, Sweden, Italy, UK, France belong to national FINDIET 2012 Survey ( $n=1248$ ), Riksmaten 2010 study ( $n=1352$ ), INRAN-SCAI-2005 ( $n=2072$ ), NDNS rolling program 2008–2012 ( $n=1378$ ), INCA-2 study 2006–2007 ( $n=2253$ ) to analyse and compare the dietary modifications required to achieve a nutritionally adequate diet with reduced GHGe, where estimates for women from all countries except Finland showed the need to increase fish intake in nutritionally optimised diets or in combined nutritional adequate and moderate GHGe reduction models; while similar trends have been observed for men from France, Italy and Finland, those from UK and Finland showed an opposite trend (Vieux et al. 2018). In Netherland in 2015, data from participants belong to Dutch National Food Consumption Survey (DNFCS) 2007–2010 ( $n=699$ ; 31–50 y) were analysed to evaluate GHGe, land use, an approximation of ReCiPe, fossil energy use in diet with no constraints, 33 nutrients within limits, GHGe limit and costs limit. Fish consumption increased from 9 g/d to 10 g/d in men and from 1 g/d to 10 g/d in women from the current diet to the optimised diet, with a significant reduction in GHGe (less than 0.06 kg CO<sub>2eq</sub>) without any difference in costs in men, and a slight increase in price in women (van Dooren et al. 2015). In a larger sample from the same survey ( $n=3819$ , 9–69 y) it was emphasised that fish was a key element of the diet as a source of essential nutrients such as EPA and DHA, without a possible equivalent substitute, leading to a higher consumption in both nutritional and environmental optimised models (Kramer et al. 2017). A study in Finland aims to derive a nutritionally

adequate and healthy diet that has the least deviation possible from the average observed diet of Finnish adults while aiming for a GHGe reduction of 33% and 50% starting from two non-consecutive 24-h dietary recalls and an ad hoc LCA of a representative sample of Finnish adult population from the National FinDiet 2017 Survey ( $n=1655$ , 18–74 y) showing that compared to current diet, in order to achieve a 33% reduction in GHGe there was no difference in fish consumption in male and a slight increase by 8 g/day in women, while stricter constraints aiming to a 50% GHGe reduction estimated a decrease in fish consumption by 19% in men but an increase by 20% in women (Irz et al. 2024). In Hungary, a study aiming to evaluate the contribution of food groups to the total dietary water footprint based on a 3-day dietary record analysis from a representative sample of Hungarian adult population from the Hungarian Dietary and Nutritional Status Survey's cross-sectional study ( $n=857$ ,  $\geq 18$  y) estimated *via* the "Water Footprint Network" Database observed that there was no change on fish consumption for men from current diet to every version of optimised diet, otherwise fish consumption in women was +3.5 g/day and +17.3 g/day in optimised diet with 10% and 18% of water footprint reduction, respectively (Tompa et al. 2022). In contrast, a study analysing data from the national cross-sectional survey INRAN-SCAI 2005–2006 ( $n=2098$ , 18–60 y) using three-day semi-structured food diaries and combined with previously published LCA analyses aiming to develop an optimised diet for the adult Italian population that met national dietary reference intakes while minimising GHGe showed that in the optimised diet, total fish intake was reduced compared with the observed diet, from 48.8 g/day in males and 45.0 g/day in females to 20.0 g/day in both sexes; however, fresh fish consumption remained relatively stable, decreasing modestly from 25.0 g/day in males and 25.5 g/day in females to 20.0 g/day, while intake of crustaceans, shellfish, mussels, and preserved fish was reduced from 16.6 g/day and 7.3 g/day in males, and 13.4 g/day and 6.2 g/day in females, to 0 g/day in both sexes (Ferrari et al. 2020).

Among studies conducted outside Europe, an analysis of the GHGe from the average Australian diet assessed through a 24-h recall and FFQ of participants of the most recent National survey of Australia adults—the 1995 Australian National Nutrition Survey ( $n=13800$ ,  $>2$  y) showed that fish consumption was 24 g/d with GHGe of 0.12 kg CO<sub>2</sub> in average diet while instead was 30 g/d with GHGe of 0.22 kg CO<sub>2eq</sub> in the recommended diet scenarios (Hendrie et al. 2014). Similarly, a study conducted in Lebanon, used data

from a nationally representative sample of adults ( $n=2177$ ,  $\geq 20$  years) to develop a healthy and sustainable dietary model aimed to reduce environmental impacts, including GHGe, water use and energy use, with dietary intake collected using a 24-h multiple-pass food recall (five-step approach), while environmental impacts were estimated through LCA analyses showed in the optimised dietary scenario, reductions in GHGe, as well as in energy, land and water use, were achieved alongside an increase in fish consumption to 22.4 g/day, corresponding to a 41% increase compared with the national average intake (Hwalla et al. 2021). Also in China, a study aims to quantify carbon footprints and minimise GHGe emissions using a method of uncertainty optimisation while meeting health requirements of a representative sample of Chinese population ( $n=11,160$ , 18–50 y) reported that finfish and shellfish consumption should increase from current dietary pattern to meet the Optimal diet of National Food-Nutrition Plan (NFNP) 2020 from about 30 g/d to 34 g/d in men and from about 28 g/d to 34 g/d in women (Song et al. 2017). Additional evidence published for Japan, a study aims to explore more sustainable Japanese diets that are with low GHGe and emphasis on cultural acceptability of a sample of healthy Japanese adults ( $n=369$ , 20–69 y) showed that fish consumption was always higher in environmental-efficient diets compared to the observed diets (Sugimoto et al. 2022). In Brazil, a study aims to identify the dietary changes to improve nutrition and reduce diet-related GHGe using ad hoc LCA estimation from two non-consecutive 1103-item food records of participants belong to the Household Budget Survey (HBS) and the National Dietary Survey (NDS), showed that in a "flexitarian" model, fish and seafood quantities increased with GHGe reduction up to about 40% and then decreased to about 40 g with stronger boundaries for GHGe reductions; also other optimised models, including in line with WHO guidelines for non-communicable chronic disease and optimised to meet mineral and vitamin requirements, consumption of fish resulted increased (Verly et al. 2022).

Despite these commonalities, the direction of change in fish consumption is not uniform across all environmental scenarios. When models impose stringent GHGe reduction targets, particularly reductions of 33–50%, fish consumption may decline rather than increase, even when nutritional adequacy is maintained. In such scenarios, reducing consumption of high-impact seafood can become necessary to remain within environmental thresholds. Illustratively, another study from the DNFCS ( $n=1402$ , 19–50 y) estimated

that achieving a 50% reduction in GHGe required a reduction of up to 23 g/day of fish, despite earlier increases under purely nutritional optimisation conditions (van de Kamp et al. 2018). Conversely, in order to overcome vitamin D shortfalls while minimising carbon footprint, fish intake has been estimated to necessarily be increased to meet nutrient requirements, leading to a necessary increase in diet's GHGe (Bruins and Létinois 2021). Furthermore, a study from the Longitudinal Ageing Study Amsterdam cohort (LASA) ( $n=1354$ ) examining Dutch dietary transitions in representative Dutch community-dwelling older adults (56–101 y) from a 254-item FFQ found that in order to reduce by 50% GHGe, weekly fish portions needed to be reduced by 36% for men and 33% for women, underscoring the significant impact of environmental constraints on allowable fish intake (Grasso et al. 2021). Contrasting data has been also reported from a representative sample of French adults (INCA-2 survey 2006–2007,  $n=1816$ ) used to model a sustainable diet optimised as nutritionally adequate while having a 30% reduced carbon impact with minimal change from the actual observed diet and isocaloric content: from the reported 33 g/d of fish and seafood intake in the actual observed diet, there was estimation of no significant change in the optimised diet (Gazan et al. 2022). Similarly, estimates from NutriNet-Santé cohort ( $n=29,413$ ) in a study aiming to model nutritionally adequate and culturally acceptable optimised diets ensuring a gradual reduction in GHGe showed that from the observed to a nutritional optimised diet with 0% reduction in GHGe, a decrease of 45% in fish consumption in all optimised diets (estimated to be equal to  $-23$  g/d of fish intake) was needed in order to reach a reduction in GHGe by 50% (Kesse-Guyot et al. 2021).

### **Environmental impact of fish consumption in modelled diets**

Modelling efforts estimating the environmental impacts of diets similarly pointed to significant increases in fish consumption in several contexts. Pescatarian or plant-forward diets in these models further elevate fish intake relative to baseline diets while reducing overall environmental impact through the removal of meat; in these scenarios, higher fish consumption is compatible with lower GHGe because emissions associated with meat are substantially reduced. Table 1.

A landmark modelling analysis aiming to estimate global GHGe per capita, per serving, and per g protein for different food groups and dietary patterns

showed that fish had a relatively high impact if compared to most food groups except livestock meat; compared to the average global diet of 2009, the 2050 global-average per capita income-dependent diet would have 82% more fish and seafood, with the pescatarian diet having a higher fish consumption than the unmodified diet in 2050 with similar GHGe from fish and seafood consumption to those in 2050, with a substantial reduction in environmental burdens if meat would be removed (Tilman and Clark 2014). Among other previously published studies exploring environmental impacts in modelling diet, an early study conducted in the UK aimed to evaluate whether adherence to dietary recommendations for health could contribute to a reduction in diet-related GHGe using mathematical modelling. Dietary data were obtained from the UK National Diet and Nutrition Survey databank, while GHGe values were assigned based on LCA data from pre-existing studies. In the resulting sustainable diet scenario, fish accounted for 11.5% of total diet-related GHGe, with an estimated consumption of 147 g/week of white fish (coated), 49 g/week of shellfish, and 91 g/week of oily fish, resulting the only animal product incremented compared to current diet (Macdiarmid et al. 2012). Concerning specific European countries, a study modelling the sustainability of various dietary patterns for Spain (including a Mediterranean diet model and current diet modelled from FAO food balance sheets and the Household Consumption Surveys of the Spanish Ministry of Agriculture, Food and Environment) in terms of GHGe, land use, energy and water consumption; in various contexts, fish contributed to total footprints about 5–10% in energy consumption and GHGe, impacting considerably less and meat and dairy representing the lowest-impact animal product among those analysed (Sáez-Almendros et al. 2013). Another early study aiming to estimate environmental impacts of food consumption in the years 1985–89 and 2006 in Germany as well as of several dietary recommendations and dietary styles based on data from the National Nutrition Surveys (NNS I 1985–1989  $n=25,000$ , 4–94 y; NNS II 2006  $n=19,000$  14–80 y) through attributional input-output LCA, fish consumption would maintain a stable environmental footprint or slightly increased since substituting more impacting food groups (i.e. meat) in modelled diets in line with various dietary recommendations, while the overall GHGe and NH<sub>3</sub> emissions would be reduced (Meier and Christen 2013). In the following year in Denmark, data from Average Danish Diet and an Ideal New Nordic Diet were elaborated to compare how much the change from these

**Table 1.** Summary results from studies including information on environmental contribution of fish in the diet.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Scarborough et al. (2014)	UK	Participants belong to EPIC-Oxford cohort (n=65000, > 20y)	130-item FFQ	Previously published database.	Estimate the difference in dietary GHGe between self-selected meat-eaters, fish-eaters, vegetarians and vegans.	Compared to fish eaters, mean dietary GHGe were 46% higher in women and 51% higher in men for meat eaters. Fish-eaters have a mean GHGe per 2000 kcal by diet type and sex of 3.91 kgCO <sub>2eq</sub> adjusted for age and sex compared to 7.19 kgCO <sub>2eq</sub> of high meat-eaters, 5.63 kgCO <sub>2eq</sub> of medium meat-eaters and 4.67 kgCO <sub>2eq</sub> of low meat-eaters.
Biesbroek et al. (2018)	Netherlands	Participants belong to EPIC-NL cohort (n = 36209; 20–70 y)	178-item FFQ	<i>ad hoc</i> LCA estimation.	To investigate the association between dietary patterns and environmental impact (GHGe).	A higher adherence to a "plant-based pattern" was characterised by consumption of 14 g/d of fish (higher compared to other dietary patterns), but also lower GHGe and higher nutritional quality.
Murakami and Livingstone (2018)	UK	Representative adults in the National Diet and Nutrition Survey 2008–09 and 2013–14 (n = 3502)	4 consecutive-day dietary diary	<i>ad hoc</i> LCA estimation.	Impact of current food consumption on GHGe.	Actual consumption of fish had a relatively important impact on GHGe (about 6 %) as compared to other food groups.
Naja et al. (2018)	Lebanon	Representative sample of the Nutrition and Non-Communicable Disease Risk Factor Survey 2008–2009 (n = 337, > 18 y)	61-item FFQ	Previously published LCA analyses.	Evaluate and calculate the Environmental Footprints of food consumption patterns among Lebanese adult population.	Fish is only included in "High Protein" dietary pattern. Water use for fish was 3.22 ± 7.76 L/day, energy use was 19.50 ± 17.89 MJ/day, GHGe was 6.86 ± 11.06 kgCO <sub>2eq</sub> /day.
Seconda et al. (2018)	France	Representative sample belong to the NutriNet-Santé Cohort (n = 34193, mean age 53.3 y)	264-item organic semi-quantitative FFQ	DIALECTE tool.	To describe observed diets with different levels of GHGe.	In the NutriNet-Santé Study, participants with a medium-impact diet (Q3), characterised by GHGe of 1229–1589 kgCO <sub>2eq</sub> /year, reported the highest fish consumption (52.6 g/day), compared with those following a low-impact diet (Q1; 347–816 kgCO <sub>2eq</sub> /year) and a high-impact diet (Q5; 2318–4099 kgCO <sub>2eq</sub> /year), whose fish consumption was 36.6 g/day and 48.5 g/day, respectively. Fish contribution to total diet related GHGe was about 4% in the lowest quintile (Q1), meanwhile about 1–2% in the highest quintile (Q5).
Biesbroek et al. (2019)	Netherlands	Participants belong to EPIC-NL cohort (n = 8932; 18–65 y)	178-item FFQ at baseline; 160-item FFQ at follow-up	<i>ad hoc</i> LCA estimation using Life Cycle Inventory (LCI) data (Blonk Consultants, data set version 2016) from Agri-Footprint.	To describe the environmental impact, expressed as GHGe, associated with the observed differences in dietary quality over 20 years in both men and women.	Fish consumption increased from baseline to follow-up in both men and women. In men, intake rose from 4.2 to 13.6 g/1000 kcal, while in women it increased from 5.8 to 16.8 g/1000 kcal. As a consequence, fish-related GHGe also increased, from 0.04 to 0.13 kgCO <sub>2eq</sub> /1000 kcal in men and from 0.05 to 0.16 kgCO <sub>2eq</sub> /1000 kcal in women.

(Continued)

Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Mertens et al. (2019a)	Denmark, Czech Republic, Italy, France	Participants belong to National Survey on Diet and Physical Activity 2005–2008 ( $n = 1739$ ), SISP04 2003–2004 ( $n = 1666$ ), INRAN-SCAI 2005–2006 ( $n = 2313$ ), INCA-2 study 2006–2007 ( $n = 2276$ ) (all MF, > 18 y)	7-d diet record on consecutive days, 24-h recall spaced over three-to-five months, 3-d diet record on consecutive days, 7-d diet record on consecutive days	SHARP Indicators Database (SHARP-ID).	Evaluate diet-related GHGe and land use from four European countries.	Fish consumption accounted for a relatively low amount of GHGe and land use across countries; however, was observed that for every 4% increase in energy intake from fish (about 60 g per day, equivalent to about half a serving per week) there was a significant increase in GHGe (+7%), but no significant impact on land use (+2%). Differences between countries were most clearly observed for GHGe, but were not attributable to country-specific factors.
Mertens et al. (2019b)	Netherlands	Representative sample of the NQplus study ( $n = 1169$ , 20–70 y)	216-item FFQ and 24-h recall	Previously published data.	To estimate the environmental impact of diet by comparing a FFQ with a 24-h recall and to study the association between diet quality and environmental impact.	Comparing different food groups to daily intake and environmental impact, fish had a consumption of 0.7 g/d derived both from FFQ and 24-h recall and all other measures such as GHGe (%), fossil energy (%), land use (%) and pReCiPe (%) have given similar results, demonstrating the low environmental impact of fish unlike other products of animal origin, such as meat.
Rose et al. (2019)	US	Representative sample of the National Health and Nutrition Examination Survey (NHANES) 2005–2010 ( $n = 16800$ , $\geq 18$ y)	24-h dietary recall	Database based on LCA literature: Food Impacts on the Environment for Linking to Diets (dataFIELD).	To assess and evaluate environmental impact (GHGe) from individual self-selected diets.	The High-GHGe diets had greater quantities of seafood ( $0.41 \pm 0.03 \text{ oz}_{\text{eq}}/1000 \text{ kcal}$ ) instead of Low-GHGe diet ( $0.21 \pm 0.01 \text{ oz}_{\text{eq}}/1000 \text{ kcal}$ ) $p < 0.001$ . About HEI components and GHGe groups, "Seafood and plant proteins" group was higher in Low-GHGe diet ( $2.38 \pm 0.06$ ) instead of High-GHGe diet ( $1.60 \pm 0.06$ ) $p < 0.001$ .
van Bussel et al. (2019)	Netherlands	Participants belong to Nutrition Questionnaire plus (NQplus) study ( $n = 1380$ , 20–77 y)	Two 24-h dietary recalls	LCA performed by Blonk Consultants data set version 2013.	To assess GHGes, land use, fossil energy use and pReCiPe score among Dutch participants' diets.	Fish consumption is statistically higher within the high on health subgroups, compared to the low on health ones; the highest value was $32 \pm 53 \text{ g/day}$ (Sustainability low Health high subgroup) while the lowest value was $5 \pm 16 \text{ g/day}$ (Sustainability high Health low subgroup).
Vellinga et al. (2019)	Netherlands	Dutch National Food Consumption Survey (DNFCS) 2012–2016 ( $n = 4313$ , 1–79 y)	Two non-consecutive 24-h dietary recalls	<i>ad hoc</i> LCA estimation.	Impact of current food consumption on GHGe and blue water for different population age groups.	About fish, daily means of GHGe was 0.13 ( $\text{kgCO}_{2\text{eq}}$ ) and blue water use was 0.001 ( $\text{m}^3$ ) in total population with higher value for adults instead of children groups. Ratio for fish were significantly associated with higher emissions (GHGe $\beta = 0.0020$ ; blue water use $\beta = 0.002$ ) in a model that included 14 individual DHD15 components.

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Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Fresán et al. (2020)	Spain	Participants of the Seguimiento Universidad de Navarra (SUN) project ( $n=17387$ , mean age 37)	Semi-quantitative FFQ	Previously reported data by several institutions and/or research groups.	Impact of current food consumption on GHGe and the use of resources (water, land and energy).	Fish and seafood consumption increased among quartiles GHGe, water use and energy use while there was a reduction among quartiles in land use. Actual consumption of fish is statistically ( $p<0.001$ ) major in from Q1 to Q4 energy-adjusted water use model and energy-adjusted energy use model, instead is minor ( $p<0.001$ ) in from Q1 to Q4 in energy adjusted land use model.
Grosso et al. (2020a)	Italy	Participants belong to the Mediterranean Healthy Eating, Ageing, and Lifestyle (MEAL) study ( $n=2044$ , > 18 y)	Long 110-item FFQ and short FFQ	Previously published dataset.	Impact of healthy dietary patterns on resources (land, water, and energy) use and GHGe.	Who had a higher sustainability score had a higher consumption of fish (85 g/day). Fish has less impact than other animal products (about 7% of total impact in GHGe, 15% of total impact in energy use, 2–3% of total impact on water use and less than 2% of total impact in land use).
Sugimoto et al. (2020)	Japan	Japanese people ( $n=392$ ; 20–69 y)	Four-non-consecutive-day diet records	Database based on the Global Link Input-Output (GLIO) model.	To examine the relationship between diet-related GHGe and the prevalence of inadequate nutrient intake.	Fish and seafood consumption among quartiles of diet-related GHGe increases from Q1 to Q4, with a consumption of 31 g/day in the first quartile and 47 g/day in the fourth quartile; total GHGe of the diet increase also from the lowest quartile to the highest quartile, suggesting that higher fish and seafood consumption is associated with diets that have a higher overall GHGe.
Auclair and Burgos (2021)	Canada	Nationally representative sample of Canadian adults from Canadian Community Health Survey (CCHS) ( $n=13612$ , $\geq 19$ y)	24-h recall	Database of Food Impacts on the Environment for Linking to Diets (dataFIELD).	To describe the carbon footprint of self-selected Canadian diets.	Fish and shellfish contributed about 5% to the total dietary GHGe, compared to other food groups; in particular shellfish intake was greater for high compared to low-GHGe diet consumers (about +5.6 g/1000 kcal).
Rippin et al. (2021)	UK	Participants belong to myfood24 validation cohort ( $n=212$ , 18–65 y)	24-h recall	Previously reported data by several institutions and/or research groups.	Impact of 3000 food consumption on GHGe and connection to individual environmental impact.	From the analysis, diets with the highest GHGe were driven by meat and not by other animal-based foods such as fish.
Álvarez-Álvarez et al. (2024)	Portugal	Participants of the Epidemiologic Health Investigation of Teenagers in Porto (EPTTeen) ( $n=1554$ )	86-item FFQ	Previously published data.	Impact of current food consumption on GHGe, energy, land, acidification, and eutrophication.	Fish and seafood had the second highest environmental impact on GHGe (29.2 % of total impacts) while only a negligible role on other outcomes compared to other animal-based food groups.
<i>Fish consumption in environmentally optimised current diets</i>						
Vieux et al. (2013)	France	Nationally representative random sample of adults participating in the Individual and National Survey on Food Consumption (INCA2 study) ( $n=2624$ ; age > 18 y)	7-d food records	<i>ad hoc</i> LCA estimation.	GHGe of food groups, total diet and differences between the optimised models.	The results are conflicting, GHGe from fish consumption tends to be higher in optimised diets with higher nutritional quality.

(Continued)

Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Biesbroek et al. (2014)	Netherlands	Participants belong to EPIC-NL cohort ( $n = 40011$ ) (PROSPECT cohort $n = 17357$ F, 49–70y; MORGEN cohort $n = 22654$ MF, 20–59y)	178-item FFQ	<i>ad hoc</i> LCA estimation.	To investigate the associations of GHGe and Land Use of the usual diet with mortality risk.	Starting from a fish consumption of 0.4 grams per day in the usual diet with a 2.1% CO <sub>2eq</sub> consumption and 0.8% land use consumption compared to the total diet, in the modelled diet where 35g/day of meat were replaced with 35g/day of fish, a 4.5 % GHGe reduction, 9.8% land use reduction and 19% mortality risk reduction was observed.
Hendrie et al. (2014)	Australia	Participants of the most recent National survey of Australia adults—the 1995 Australian National Nutrition Survey ( $n = 13800$ , > 2y)	24-h recall and FFQ	Environmentally extended input-output model of the Australian economy AUS-MRIO.	GHGe from the average Australian diet, from core foods and non-core foods.	Fish consumption was 24g/d with GHGe of 0.12 kgCO <sub>2eq</sub> in average diet while instead was 30g/d with GHGe of 0.22 kgCO <sub>2eq</sub> in recommended diet scenarios (both total diet and foundation diet).
Van Dooren (2015)	Netherlands	Participants belong to Dutch National Food Consumption Survey 2007–2010 ( $n = 699$ ; $M = 348$ , $F = 351$ , 31–50y)	No data	<i>ad hoc</i> LCA estimation.	GHGe, land use, an approximation of ReCiPe, fossil energy use in diet with no constraints, 33 nutrients within limits, GHGe limit and costs limit.	Fish consumption increased from 9g/day to 10g/day in men and from 1g/day to 10g/day in women from the current diet to the optimised diet, energy consumption also follows the same trend. GHGe is less than 0.06 kgCO <sub>2eq</sub> in the optimised diet without any difference in cost in men, in women we have no difference in GHGe but an increase of 0.07 euros.
Horgan et al. (2016)	UK	National representative cross-sectional survey of adults of the National Diet and Nutrition Survey 2008–11 ( $n = 1491$ )	4-day diet diary	GHGe values based on LCA from the most comprehensive dataset available in the UK.	Modelling of sustainable and healthy dietary recommendations with 25% GHGe reduction.	Fish has been one of the most commonly added foods in the dietary pattern. To achieve optimal intake of white fish and oily fish for sustainable and healthy diets target it was necessary to add about 10g/day of white fish and 25g/day of oily fish.
Perignon et al. (2016)	France	Nationally representative of French adults ( $n = 1899$ , > 18y)	7d food records	Hybrid input-output LCA method.	To evaluate the compatibility between reduction of diet-related GHGe and various dimensions of diet sustainability.	In the scenario with constraints on all nutrients (ADEQ scenario) reduction in GHGe were mainly driven by decreases in ruminant and deli meat consumption, meanwhile fish intake was preserved or increased. Within the Meat/Fish/Eggs food group, fish replaced ruminants and deli meats, promoting a 30% reduction in GHGe while keeping total Meat/Fish/Eggs intake about to 100g/day and increasing fruit and vegetable consumption.
Kramer et al. (2017)	Netherlands	Participants belong to Dutch National Food Consumption Survey 2007–2010 (DNFCS) ( $n = 3819$ , 9–69y)	24 h recalls on two non-consecutive days	GHGe, fossil energy use and land occupation collected from various sources. LCA assessment with ReCiPe method.	To calculate pReCiPe points, GHGe, fossil energy use, land occupation of current diets, optimised diet without environmental constraints and diets at the “critical point”.	Fish remains a key element of the diet, as a source of essential nutrients such as EPA and DHA, without a possible equivalent substitute. Fish consumption was found to be higher in the “nutritionally optimized” and “critical point” model, both in men and women. Differences were found in intergender patterns between “Nutritionally optimized” and “critical point” model but not among the same gender patterns between these two optimised model.

(Continued)

Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Song et al. (2017)	China	Representative sample of Chinese population (n = 11160, 18–50y)	Food survey database	Global LCA literature database.	Quantify carbon footprints and minimise GHGe emissions using a method of uncertainty optimisation while meeting health requirements.	Finfish and shellfish consumption increase from current dietary pattern to the optimal diet of National Food-Nutrition Plan 2020 compared both for men and women, about 30.03 vs 34.52 (g/day) for men and 27.59 vs 34.52 for women (g/day). With the exception of the Nutrition-Environment model in men, in all optimised diet models, in both genders, a reduction in GHGe in g/CO <sub>2eq</sub> was observed for the fish subgroup, compared to the observed diet. On the contrary, a reduction in eutrophication levels in g/N <sub>eq</sub> was observed for fish consumption only in women, while an increase was observed in men, always starting from the observed diet.
Barré et al. (2018)	France	Participants belong to "Etude Individuelle Nationale des Consommations Alimentaires" (INCA2) study (n = 3075, > 18y)	7-day food records	Environmental consulting firm based on a hybrid input/output LCA method using international standards.	To assess the impact of introducing nutrient bioavailability and co-production links considerations on the dietary changes needed to improve diet sustainability and to estimate GHGe, atmospheric acidification, marine eutrophication.	Nutrition-Environment model in men, in all optimised diet models, in both genders, a reduction in GHGe in g/CO <sub>2eq</sub> was observed for the fish subgroup, compared to the observed diet. On the contrary, a reduction in eutrophication levels in g/N <sub>eq</sub> was observed for fish consumption only in women, while an increase was observed in men, always starting from the observed diet.
van de Kamp et al. (2018)	Netherlands	Participants belong to Dutch National Food Consumption Survey (DNFCS) (n = 1402, 19–50y)	Two 24-h recall	LCA analysis.	To determine environmental impact and nutrient intake associated with the Dutch diet.	It was observed, for both men and women, that in the "sustainable healthy consumption" scenario there was 56% less GHGe from fish consumption compared to the "regular healthy consumption" scenario.
Vieux et al. (2018)	Finland, Sweden, Italy, UK, France	Participants belong to national FINDIET 2012 Survey (n = 1248), Riksmaten 2010 study (n = 1352), INRAN-SCAI-2005 (n = 2072), NDNS rolling program 2008–2012 (n = 1378), INCA2 study 2006–2007 (n = 2253); all 18–64 y	48-h recall with two replicates, 4-d dietary records, 3-d dietary records, 4-d dietary records, 7-d dietary records	Previously published data.	To analyse and compare the dietary modifications required to achieve a nutritionally adequate diet with reduced GHGe in five European countries.	About women France, UK and Italy substantially had to increase fish consumption compared to the observed diets (OBS) with a substantial equivalence between the Nutritional model (NUTR) and the Nutritional-GHGe-30% model (NUTR-GHGe-30%); a similar trend was found in Sweden where, despite a reduction in the NUTR compared to the OBS, there had to be an increase in fish consumption in the NUTR-GHGe-30% model; on the contrary, in Finland the two modified models detected the same reduction in fish consumption compared to the OBS. About men France, Italy and Finland had the same trend compared to women. Instead the UK and Finland showed an opposite trend.
de Gavelle et al. (2020)	France	Adult participants of the Second Individual National Study on Food Consumption (INCA2) 2006–2007 (n = 1678, 18–65 y)	7-d food record	Previously published LCA analyses.	To explore and compare the dietary changes needed in order to reach a nutritionally adequate diet with 10% lower GHGe.	In both scenario with no constraint (SN) and scenario for constrained by an increase in the plant:animal protein ratio (SP) models, an increase in oily fish consumption was observed in both men and women compared to the observed diet, accompanied in the SP model by a reduction in GHGe.

(Continued)

Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Perignon et al. (2019)	Tunisia	Representative sample from nationally cross-sectional survey as part of the Transition and Health Impact in North Africa (TAHINA) project ( $n=7209$ , 35–70y)	138-item FFQ	Life cycle vision using a hybrid method that combine trade statistic and production data.	To determine diets that are nutritionally adequate, culturally suitable, and with low environmental impact.	The total amount of Meat/Fish/Eggs does not change between the observed diet and the modified diets, but looking at the components we have an intra-group substitution in favour of fish consumption of 15%.
Reynolds et al. (2019)	UK	Participants belong to The 2013 Family Food Module of The Living Costs and Food Survey ( $n=5144$ )	2013 LCFS collected data	Previously published data.	To model diet that meet dietary requirements for health and reduce GHGe (57 and 80% targets) by income quintile.	In order to reach GHGe target of 1.78 kgCO <sub>2eq</sub> /person per day fish purchases had to increase from 16 and 19 g/day respectively from low income and high income in 2013 diet to 39 g/day in the optimised diet both low and high income.
Broekema et al. (2020)	Netherlands	Representative adults in the Dutch National Food Consumption Survey (DNFCS) ( $n=699$ ; 31–50y)	Two independent 24-h dietary recalls	<i>ad hoc</i> LCA estimation.	Identify diets that satisfied nutritional requirements and remained below GHGe targets but deviated minimally from the baseline diet among Dutch adults.	To achieve a nutritionally adequate diet with no limits on GHGes (no-GHGe-target scenario), differences with the baseline diet among Dutch adults were a higher consumption of fish and shellfish; fish consumption was even higher in the GHGe-target scenario, 2030 and 2050 scenario (from 18 g/day baseline to 54 g/day GHGe scenario).
Ferrari et al. (2020)	Italy	Participants belong to the national cross-sectional survey INRAN-SCAI 2005–2006 ( $n=2098$ , 18–60 y)	3-day semi-structured diary; INRAN-SCAI 2005–2006 food database	Previously published LCA analyses.	To develop an optimised diet for the adult Italian population, and to describe a nutritionally optimal food consumption pattern that meets the national dietary reference intakes while minimising GHGe.	In the optimised diet, total fish intake was reduced relative to the observed diet, from 48.8 g/day in males and 45.0 g/day in females to 20.0 g/day in both sexes. Fresh fish consumption remained largely stable, with a modest decrease from 25.0 g/day (males) and 25.5 g/day (females) to 20.0 g/day. Conversely, the intake of crustaceans, shellfish, mussels, and preserved fish was entirely eliminated, declining from 16.6 g/day and 7.3 g/day in males, and 13.4 g/day and 6.2 g/day in females, to 0 g/day in both sexes.
Grasso et al. (2021)	Netherlands	Representative of Dutch older adults (56–101y) belonging to the Longitudinal Ageing Study Amsterdam cohort (LASA) ( $n=1354$ )	254-item FFQ	<i>ad hoc</i> LCA estimation.	Identify dietary changes that deviate least from habitual intake and increase protein intake in the context of the 2015 Dutch food-based dietary guidelines (FBDG) while reducing diet-associated GHGes in Dutch community-dwelling older adults.	From the usual diet to the +PROT and +PROT-GHGe-50 diets it is clear that it is necessary to reduce about 36% for men and 33% for women the portions of fish consumed weekly.
Mertens et al. (2020)	Denmark, Czech Republic, Italy, France	Participants belong to DANSDA ( $n=1385$ ), SISP04 ( $n=1386$ ), INRAN-SCAI ( $n=1978$ ) and INCA-2 study ( $n=1713$ )	7-d diet records on consecutive days; two 24-h recalls spaced over three to five months; three day-day diet records on consecutive days; 7-d diet records on consecutive days	Standardised LCA database.	Explore the nutritional and GHGe impacts of meat replacers.	An increase in fish consumption was observed in all dietary patterns, both meat replaced and fortified, but the impact of this increase differed across countries and also between the different types of optimised diets.

(Continued)

Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Bruins and Léimois (2021)	Netherlands	Dutch people	24-h dietary recall Dutch National Food Consumption Survey (DNFCS) 2003	Data collected from LCA database, Optimeal 2.0 and Agri-footprint 3.0 Life Cycle inventory food database.	To model dietary changes in a Dutch "model diet" to overcome vitamin D shortfalls while minimising carbon footprint.	In the first scenario (optimising diet for vitamin D without energy constraints) an increase in the carbon footprint of the optimised diet compared with the baseline diet was attributable to an increase in the carbon footprints of fish (15-fold), substantially contributing to the nearly 3-fold increase in total carbon footprint. In the second scenario (within energy constraints of 2000kcal) achieving higher vitamin D intakes required a 7-fold increase in fish-related carbon footprint and nearly a 10-fold increase in energy derived from fish. In the third scenario (additional fortified foods for vitamin D) optimising the diet involved an 8% increase in the total diet carbon footprint, with an increase of 8-fold for fish. In the fourth and last scenario (additional fortified foods for vitamin D and reduction in CO <sub>2</sub> ) fish consumption had to be increased to meet nutrient requirements, but this led to a substantial increase in the diet's carbon footprint.
Hwalla et al. (2021)	Lebanon	Nationally representative sample of Lebanon individuals (n=2177, ≥ 20y)	24-HR multiple pass food recall (MPR) 5-step approach	LCA analysis based on published and reviewed data.	To model an healthy and sustainable diet while reducing environmental impact (GHGe, water use, energy use).	To reduce GHGe, as well as energy, land and water use, fish consumption in the optimised diet increased to 22.4g/day, representing a 41% increase compared with national average consumption.
Kesse-Guyot et al. (2021)	France	NutriNet-Santé cohort (adults enrolled on a voluntary basis, n=29413)	Semi-quantitative 264-item FFQ	DIALECTE tool.	Modelling of nutritionally adequate and culturally acceptable optimised diets ensuring a gradual reduction in GHGe.	From the observed to a nutritional optimised diet with 0% reduction in GHGe, the authors estimated a decrease of 45% in fish consumption in all optimised diets; in order to reach a reduction in GHGe by 50%, the authors estimated a gradual decrease up to -23g/day of fish consumption.
Verly et al. (2022)	Brazil	n=32746 (≥ 10y) participants belong to the House-hold Budget Survey (HBS) and the National Dietary Survey (NDS) (n=55970 households HBS, n=13569 households NDS)	Two non-consecutive 1103-item food records	ad hoc LCA estimation based on the "Environmental Footprints of Food and Culinary Preparations Consumed in Brazil" database.	Identify the dietary changes to improve nutrition and reduce diet-related GHGe.	In the FLEX model, fish and seafood quantities increased with the GHGe reduction up to about 40% and then decreased to about 40g with stronger GHGe reductions. Even in CND model (WHO guidelines for non-communicable chronic disease) and in NUT model (mineral and vitamin requirements) there was more fish than the observed diet.
Gazan et al. (2022)	France	Representative sample of French adults (INCS2 survey 2006–2007, n=1816)	7-day dietary record	SUStable database.	Modelling of sustainable diet optimised as nutritionally adequate while having a 30% reduced carbon impact with minimal change from the actual observed diet and isocaloric content.	From the reported 33g/day of fish and seafood intake in the actual observed diet, there was estimation of no significant change in the optimised diet.

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Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Kesse-Guyot et al. (2022)	France	NutriNet-Santé cohort (adults enrolled on a voluntary basis, $n = 29326$ )	Semi-quantitative 264-item FFQ	Environmental indicators related to food production were computed using LCA using the DIALECTE database.	To optimise and compare 6 types of diets considering environmental indicators such as GHGe, cumulative energy demand, land occupation.	The consumption of fish was within the target values of the EAT-Lancet diet. The final optimised model shows significant increases in fish consumption among all observed starting diet types.
Sugimoto et al. (2022)	Japan	Representative sample of healthy Japanese adults ( $n = 369$ , 20–69 y)	4-d dietary record data	Newly developed database using a global input-output model in Japan and the standard tables of food composition in Japan.	Explore more sustainable Japanese diets that are with low GHGe and emphasis on cultural acceptability.	Significant differences in fish intake were found in both men and women between DEA-efficient and DEA-inefficient diets, showing that fish consumption was always higher in DEA-efficient diets. The same trend is observed between the observed diets and the MIN-GHGe diets.
Tompa et al. (2022)	Hungary	Representative of Hungarian adult population from the Hungarian Dietary and Nutritional Status Survey's cross-sectional study ( $n = 857$ , $\geq 18$ y)	3-day dietary record analysis	"Water Footprint Network" (WFN) Database.	Contribution of Food Sub-Groups to the Total Dietary Water Footprint (WFP).	It was observed that there wasn't any change on fish consumption for men from current diet to every version of optimised diet, otherwise fish consumption in women was +3.5 g/day in optimised diet with 10% of WFP reduction, +17.3 g/day in optimised diet with 18% of WFP reduction.
Nordman et al. (2023)	Denmark	Representative sample of Danish adults of Danish National Survey of Diet and Physical activity (DANSDA) ( $n = 2492$ adults; 51.8% W; 18–64 y, mean age 42.8 years).	7-day pre-coded food diary	GHGe values based on LCA from pre-existing databases.	Derive a nutritionally adequate and healthy diet that has the least deviation possible from the average observed diet of Danish adults while aiming for a GHGe reduction of 31%.	From the reported 36 g/day of fish and shellfish intake in the actual observed Danish diet, there was an increase equal to 46 g/day in the Nutri-Health-GHGe diet. The total amount of fish and shellfish was increased of 28% but there was a redistribution of the types of fish to substantially less high-GHGe fish in support of increased amounts of fatty fish.
Eustachio Colombo et al. (2024)	Sweden	Representative sample of Swedish adults from Swedish dietary survey Riksmaten Vuxna 2010–11 ( $n = 1797$ , 18–80 y)	Web-based 4-day diary	Climate Database developed and maintained by the Research Institutes of Sweden (RISE).	Calculate $CO_{2eq}$ emission between EAT Lancet diet and different version of optimised diet elaborated using Swedish dietary data.	Every version of optimised diet was higher in Fish consumption as compared of EAT-Lancet diet (about 5% vs about 2% of daily estimated energy requirement).
Irz et al. (2024)	Finland	Representative Sample of Finnish adult population from The National FinDiet 2017 Survey ( $n = 1655$ , 875 F – 780 M, 18–74 y)	Two non-consecutive 24-h dietary recalls	GHGe coefficients were generated using Life LCA. The total amount of MFE does not change between the observed diet and the modified diets, but looking at the components we have an increase in fish consumption of 15%.	Derive a nutritionally adequate and healthy diet that has the least deviation possible from the average observed diet of Finnish adults while aiming for a GHGe reduction of 33% and 50%.	From current FinDiet 2017 to GHGe –50% diet, changes for male is –19% and for women +20% of fish consumption; otherwise, compared to GHGe –33% diet. About difference in g/cap per day, there isn't any change for men from initial diet to GHGe –33% diet, instead of women where the consumption is higher of 8 g/cap per day.

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Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Lengle et al. (2024)	Norway	Participants belong to the Norkost 3 survey 2010–2011 ( $n=1787$ , 18–70 y)	24-dietary recall	Previously published LCA analyses.	To describe dietary environmental impacts of Norwegian adults on global warming potential, freshwater and marine eutrophication, terrestrial acidification, water use and land use.	Fish and shellfish accounted for approximately 2–3% of total daily energy intake and contributed about 3–4% to global warming potential, 3–4% to freshwater eutrophication, 5–7% to marine eutrophication, and 3–4% to terrestrial acidification. Their contribution was lower for resource-use indicators, amounting to about 2–3% of water use and 1–2% of land use.
<i>Environmental impact of modelling diet</i> Macclarmid et al. (2012)	UK	[no data]	UK National Diet and Nutrition Survey databank	GHGE values based on LCA from pre-existed works.	To describe if following dietary requirements for health can lead to reduction in GHGE by using mathematical modelling.	In the final sustainable diet fish represents 11.5% of total GHGe of the diet; in particular with a consumption of 147 g/week of white fish (coated), 49 g/week of shellfish and 91 g/week of oily fish.
Meier and Christen (2013)	Germany	Participants belong to National Nutrition Surveys (NNS I 1985–1989 $n=25000$ , 4–94 y; NNS II 2006 $n=19000$ 14–80 y)	24-h dietary recalls	Attributional Input-Output LCA/hybrid-LCA and top-down input-output tables of System of Environmental and Economic Accounting (SEEA).	Environmental impacts of Food Consumption in the Years 1985–89 and 2006 in Germany As Well As of Several Dietary Recommendations and Dietary Styles Based.	Fish consumption in the two national surveys increased in 2006 compared to 1985, however the total environmental impact decreased on average in the 2006 survey for both GHGe, $NH_3$ , land use and primary energy use; stratifying for the various dietary styles, fish consumption remained stable compared to the 2006 survey but the total environmental impact decreased, especially for dietary styles more adherent with the guidelines (such as D-A-CH or UGB).
Sáez-Almendros et al. (2013)	Spain	A representative sample of the Spanish population from the Household Consumption Surveys of the Spanish Ministry of Agriculture, Food and Environment ( $n=6000$ )	Daily food purchases and monthly purchases; FAO food balance sheets.	Previously published data.	Sustainability of the Spanish Mediterranean dietary pattern in terms of GHGe, land use, energy consumption and water consumption.	Fish contribution to the Mediterranean dietary pattern intake was about 2% compared to other food groups; has a relative contribution to total footprints about 9% in energy consumption and GHGe. In addition, fish was one of the food groups with the highest contribution to energy intake and it was the third contributor to GHGe emissions in all the patterns analysed (Mediterranean dietary pattern, Spanish dietary pattern, Western dietary pattern).
Saxe (2014)	Denmark	Average Danish people	Average Danish Diet and Ideal New Nordic Diet .	Danish-LCA food database, Ecoinvent database version 2.2 and literature.	To compare how much the change from Average Danish Diet to New Nordic Diet impacts different environmental and human health categories such as respiratory inorganics, nature occupation, global warming and sum of 13 other impact categories and also evaluate the socio-economic cost of this change.	Fish consumption increases by 138%, from 11.7 kg x person $-1 \times y -1$ of which 54% is imported in the Average Danish Diet while in the New Nordic Diet it will be 29 kg with 0 imported, with a difference of 238%.

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Table 1. Continued.

Author, year	Country	Population description	Dietary information	Tools used to assess environmental impact	Environmental outcomes	Main findings
Tilman and Clark (2014)	Global	[multiple possible data]	[multiple possible data].	LCA analysis based on published and reviewed data.	To calculate and estimate GHGe per protein, per servings and per kcal of various food groups and GHGe per capital and global for different dietary pattern.	Relative to the average global diet of 2009, the 2050 global-average per capita income-dependent diet would have 82% more fish and seafood. The pescatarian diet has a higher fish consumption than the unmodified diet in 2050 and would have similar GHGe from fish and seafood consumption to those in 2050 but by removing meat it would have a lower environmental impact. Higher fish intake is the hardest to achieve for all diets.
van Dooren et al. (2014)	Netherlands	Average Dutch women (22–50y)	Dutch National Food Consumption Survey (VCP) 1998 about average Dutch consumption and other guidelines.	LCA methodology previously described in the Agri-footprint method.	GHGe and land use per day according to the six diets.	
Tyszler et al. (2016)	Netherlands	Average Dutch active women (n=3819, 31–50y)	Dutch Consumption Panel survey population	Data collected from various sources and modelled from cradle to grave, including retail phase, the consumer phase, and end of life of packaging materials.	To estimate GHGe, fossil energy use, land occupation, pReCIpe per day in different diet types.	In Closest healthy, Vegetarian M and 30% less model fish consumption increased compared to current diet pattern; both GHGe and land occupation decrease, pReCIpe score remains the same and fossil energy use increase.
Eustachio Colombo et al. (2021)	Sweden	Participants belong to the Swedish national dietary survey Riksmaten Adolescents 2016–2017 (n=3099, 10–18 y)	Web-based 24-h recall method (RiksmatenFlex) on two non-consecutive days	Climate Database from Research Institute of Sweden (RISE).	Designing nutritionally adequate and culturally acceptable diets with significantly reduced GHGe based on the current diet of adolescents in Sweden.	Fish consumption grow up from about 2% in EAT Lancet model diet to about 6% in Pesc+ diet and other optimised diet. Anyway, seafood had an increase from the baseline diet 44.8g/day to +32.2% in Omni diet until +71.9% in Pesc+.
Castaldi et al. (2022)	Seven Mediterranean countries (Cyprus, Croatia, Greece, Italy, Portugal, Spain and Malta) and other 21 European countries	NA	FAOSTAT food balance database	Data collected from Su-Eatable LIFE (SEL) database.	To evaluate the adherence of the Mediterranean Diet to global EGHe reduction targets.	In the Mediterranean countries (7MED) GHGe from fish and shellfish consumption were higher (about 145 kg CO <sub>2eq</sub> capita <sup>-1</sup> year <sup>-1</sup> ) compared with the other EU countries (21OTHER) (about 85 kg CO <sub>2eq</sub> capita <sup>-1</sup> year <sup>-1</sup> ).
Tucci et al. (2024)	Italy	NA	NA	Su-Eatable LIFE (SEL) database.	To describe the environmental sustainability of the new MED-EAT-IT dietary pattern.	Seafood consumption in the new dietary pattern increased from 40 to 67 kcal/day (+68%), however, this substantial rise was associated with only a modest increase in carbon footprint (+12.2%), while the water footprint decreased by 6.3%.

two models would affect different environmental outputs: fish consumption increases by 138%, from 11.7 kg/person/year (of which 54% estimated to be imported) to 29 kg with 0 imported, with a higher contribution of fish to the environmental footprint but included in an overall lower impacting dietary pattern (about 65–70% of respiratory inorganics, nature occupation, and global warming) (Saxe 2014). In the Netherlands, a study aimed to estimate GHGe and LU per day according to the six diet models based on dietary guidelines for Dutch women (22–50 y), the Mediterranean diet or other dietary patterns showed that the Mediterranean and the Dutch Dietary Guidelines were characterised by the highest fish intake (37 g/day) but only the former had an acceptable health and sustainability score (van Dooren et al. 2014). Another group of researchers working on the same topic aiming to model a healthy and sustainable diet showed that in the “closest healthy”, pesco-vegetarian, and 30% reduction in the pReCiPe score models, fish consumption increased compared to current diet pattern, with GHGe, land occupation, and pReCiPe scores decreasing while fossil energy use increased in the pesco-vegetarian model (Tyszler et al. 2016). A more recent study conducted in 2022 evaluated the adherence of the Mediterranean Diet to global targets for the reduction of environmental GHGe across seven Mediterranean countries (Cyprus, Croatia, Greece, Italy, Portugal, Spain and Malta) in comparison with 21 other European countries modelled on FAOSTAT food and balance database, while environmental impacts were analysed using data collected from Su-Eatable LIFE (SEL) database. In the Mediterranean countries, GHGe attributable to fish and shellfish were higher than those observed in the other European countries, reaching approximately 145 Kg CO<sub>2eq</sub>/capita/year compared with about 85 Kg CO<sub>2eq</sub>/capita/year in other EU countries, reflecting a greater contribution of seafood to diet-related emissions within Mediterranean dietary patterns (Castaldi et al. 2022). Finally, a more recent study evaluated the environmental sustainability of an adaptation of the EAT-Lancet planetary diet to the Italian population from current national dietary guidelines using the Su-Eatable LIFE (SEL) database to assess the carbon and water footprints showed that seafood consumption would increase from 40 to 67 kcal/day (+68%) associated with only a modest increase in carbon footprint (+12.2%), while decreasing the water footprint by 6.3% (Tucci et al. 2024). A study aiming to design nutritionally adequate and culturally acceptable diets with significantly reduced GHGe based on the current diet of adolescents in Sweden through a

web-based 24-h recall method (RiksmatenFlex) on two non-consecutive days from participants belonging to the Swedish national dietary survey Riksmaten Adolescents 2016–2017 ( $n = 3099$ , 10–18 y), fish consumption increased from the baseline diet to up to 70% in pescatarian optimised models (corresponding to up to 5% of daily energy intake) (Eustachio Colombo et al. 2021). However, the differences in predicted fish consumption depending on the environmental constraint modelation level underscore the complexity of integrating fish into sustainable dietary frameworks and highlights the importance of environmental boundary targets in dietary policy and planetary health modelling.

## Discussion

This review synthesises evidence from observational cohorts, environmental footprint analyses, and dietary optimisation models to clarify the complex role of fish in healthy and sustainable diets. Differences in findings across studies appear to be strongly influenced by the underlying methodological approach. Observational studies, which are based on self-selected diets within specific populations, primarily reflect existing consumption patterns and therefore tend to show fish as a relatively minor contributor to overall environmental impacts, particularly when compared with higher-impact food groups such as red and processed meats. These studies provide valuable insights into real-world dietary behaviours, but their findings are inherently shaped by current intake levels, which are often below recommended amounts in many settings. Across multiple contexts, fish emerges as a food group with a comparatively favourable environmental profile relative to most animal-source foods, particularly ruminant meat, while providing essential nutrients that are difficult to obtain in sufficient quantities from non-fish sources. Fish is also consistently included in healthy plant-based (not exclusively vegetarian) dietary patterns, such as the Mediterranean diet, which in turn offer a lower environmental impact and promote various health benefits, including cardiovascular benefits (Sebastian et al. 2024; Molani-Gol and Rafraf 2025; Ungvari et al. 2025a), cancer prevention (González-Palacios Torres et al. 2023; Zhu et al. 2023; Shu et al. 2024; Ungvari et al. 2025b), and cognitive health (Fekete et al. 2025). The collective findings suggest that moderate fish consumption can simultaneously improve nutrient adequacy and lower diet-related GHGe when it displaces meat, especially red and processed meat. However, the relationship between fish consumption and environmental

sustainability is not uniformly linear or unidirectional. One of the central insights from the literature is that the environmental impact of fish may be affected by the amount consumed, overall dietary pattern, and species choice (i.e. shellfish impacting more than fish), all contributing to differences in environmental footprints. On this last matter, differences across fish species have to be taken into account when considering both environmental impact and nutrient content (Bianchi et al. 2022). While white fish tend to be low impact, some crustaceans and certain farmed species have higher GHGe (Gephart et al. 2021). This heterogeneity underlies seemingly contradictory findings across studies: for example, fish contributing only 2–7% of total GHGe in some assessments, but ranking as the second-largest contributor (29.2%) in others where seafood intake patterns differ substantially (Grasso et al. 2021; Álvarez-Álvarez et al. 2024).

In contrast, dietary optimisation models apply predefined nutritional, environmental, and sometimes economic constraints to identify theoretical diets that meet specific targets. Within these frameworks, fish intake is frequently modified to satisfy nutrient requirements (especially for nutrients such as EPA, DHA, and vitamin D) leading in many cases to increased consumption relative to baseline diets. However, when more stringent environmental constraints are imposed, particularly ambitious greenhouse gas emission reduction targets, these same models may instead reduce fish intake or shift consumption towards lower-impact species. As such, optimisation studies reflect not only biological and environmental relationships but also the structure and assumptions embedded within the models, including constraint selection, acceptability limits, and the treatment of food groups. Diet optimisation studies further underscore the conditional nature of the role of fish in sustainable diets. When models prioritise nutrient adequacy alone, fish intake almost always increases, often substantially. In Dutch, Nordic, British, and Italian populations, nutrient-optimised diets require increased fish intake relative to observed diets, reflecting the role of fish in meeting EPA/DHA requirements and improving micronutrient sufficiency. In some models, fish intake must double or even triple to achieve nutritional adequacy. When environmental constraints are added (especially stringent GHGe reduction targets) optimisation outputs shift. Mild GHGe reductions often remain compatible with increased fish consumption. However, in scenarios requiring 33–50% reductions in diet-related GHGe, fish consumption may be reduced or restructured, not because fish is inherently high-impact, but because

other elements of the diet cannot be sufficiently reduced without compromising nutrient adequacy. For example, high-impact seafood such as crustaceans or certain aquaculture products become limiting factors in GHGe-constrained optimisation, leading to reductions in total fish intake or shifts towards lower-impact species. Likewise, gender-specific optimisation results showed that women often require increased fish intake even under sustainability constraints, while men's requirements may decrease—an indication of different baseline nutrient adequacy needs and risk profiles across sexes.

An overarching theme is that fish plays a “balancing role” in sustainable diets, providing essential nutrients while exerting variable environmental pressures depending on species. Consequently, rather than asking whether fish consumption should universally increase or decrease, sustainable dietary guidance must consider which fish, how it is produced, what it replaces, and how much is required for nutrient adequacy. Policy relevance lies not in advocating blanket increases or reductions in fish consumption, but in advancing species-specific recommendations, promoting sustainable fisheries and aquaculture, and supporting dietary patterns in which fish displaces higher-impact foods. Taken together, the methodological diversity helps explain much of the apparent inconsistency in the literature. Rather than representing conflicting evidence per se, these differences highlight that the role of fish in sustainable diets is highly context-specific and sensitive to both analytical choices and underlying assumptions. A clearer interpretation of the evidence therefore requires careful consideration of study design, modelling frameworks, and the specific constraints under which results are generated. The presented findings collectively suggest that fish can be an integral component of healthy and sustainable diets, but its optimal role must be defined within the broader context of food system dynamics, species environmental performance, and nutritional needs.

This study has some strengths and limitations to be considered. To begin with, this is the first report to comprehensively summarise existing evidence on the environmental footprint of fish in current dietary intakes globally, optimised diets, and dietary models. A major strength of this review is its integration of multiple methodological approaches, which together provide a comprehensive overview of fish's environmental and nutritional roles. The included studies span diverse geographic regions and dietary cultures, allowing identification of consistent trends as well as context-specific differences. Moreover, the incorporation of modelling studies allows assessment of

counterfactual scenarios that cannot be tested empirically, providing insights into how fish intake would need to shift under different sustainability or nutritional policies. Finally, by synthesising evidence across observational and modelled contexts, this review highlights both the real-world behaviours of current diets and the theoretical requirements of optimised diets.

Nonetheless, some limitations should be acknowledged. First, substantial heterogeneity exists in LCA methodologies across studies, including system boundaries, functional units, allocation methods, and databases used. This heterogeneity can influence absolute and relative estimates of fish's environmental impact and complicates direct comparisons. Second, some of the reviewed studies included several related but not identical categories, including fish, seafood, shellfish, aquaculture products, and species-specific examples often aggregated within a single category, masking important species-level differences that can substantially alter environmental profiles. Third, dietary optimisation models rely on assumptions—such as no supplementation, fixed food acceptability constraints, or simplified environmental targets—that may not reflect real-world consumer behaviour or the complexity of food production systems. Fourth, most available evidence is derived from high-income countries; findings may not generalise to low- and middle-income contexts with different fish consumption patterns and food system structures. Fifth, only limited studies provided data on comprehensive scenarios concerning food group substitutions, which are likely to be more relatable to real-world situations. Finally, few studies integrate contaminant exposure (e.g. methylmercury) or biodiversity and ecosystem impacts of fisheries, which are critical dimensions of seafood sustainability but not well captured in GHGe-focused analyses. Taken together, these limitations highlight the need for more harmonised LCA approaches, species-specific dietary modelling, and expanded research in diverse socioeconomic settings.

## Conclusions

In conclusion, the evidence synthesised in this review suggests that fish can contribute to both human health and environmental sustainability, although its role appears to be highly context-dependent. Fish generally exhibits lower GHGe, land use, and water use than terrestrial animal-source foods, particularly red and processed meats, and replacing meat with fish is often associated with potential health and environmental advantages. These characteristics may partially explain

why fish intake increases in many nutrient-optimised dietary models. However, the environmental impact of fish varies widely by species and production system, and under stringent GHGe reduction targets, optimised diets may require reductions in high-impact seafood or shifts towards lower-impact species. Overall, the available evidence suggests that fish may meaningfully contribute to improving dietary nutrient adequacy and overall diet quality while substituting higher-impact animal-source foods, although this relationship is not uniform across all contexts. Its role within optimised diets is driven largely by nutrients that are difficult to replace, but its inclusion does not always lead to a straightforward alignment between health and environmental objectives. Besides, the health implications of fish in sustainable diets cannot be reduced to simple metrics of increased or decreased intake; instead, they must be evaluated within the complex intersection of nutritional needs, environmental targets, and dietary pattern restructuring. Ultimately, the integration of fish into sustainable diets must consider trade-offs between nutritional adequacy, environmental impact, species sustainability, and cultural dietary practices. Fish is likely to remain an important component of healthy dietary patterns worldwide, but its sustainability depends not only on how much is consumed but also on what types of fish are chosen and the ecological performance of their production systems. Future research would benefit from more detailed and harmonised assessments, including analyses disaggregated by fish species and seafood categories, improved consistency in environmental metrics, and greater integration of ecosystem-level indicators. Such efforts could help clarify the role of different types of seafood within dietary recommendations aligned with planetary health objectives.

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## Authors' contributions

CRedit: **Alberto Dolci**: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; **Alessandro Scuderi**: Validation, Writing – review & editing; **Evelyn Frias-Toral**: Validation, Writing – review & editing; **Leonardo Hernández**: Validation, Writing – review & editing; **Andrea Di Mauro**: Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing; **Fabrizio**

**Furnari:** Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing; **Alice Rosi:** Validation, Writing – review & editing; **Francesca Scazzina:** Validation, Writing – review & editing; **Giuseppe Grosso:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

## Disclosure of interest

A.D. is an employee of Bolton Food S.P.A. The other authors declare no conflicts of interest.

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## Data availability statement

All data are available within the article.

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