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Integrated Assessment of Food-System and Land-Based Environmental Impacts Under Blue Growth Scenarios

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Integrated assessment of food-system and land-based environmental impacts under blue growth scenarios

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Abstract

The integration of aquatic or 'blue' foods into global food system assessments is crucial for achieving sustainable development goals. By adapting the Global Biosphere Management Model (GLOBIOM) to account for the demand and supply of shared resources across marine and terrestrial food production systems, we assess future land-use changes and associated sustainability indicators under alternative blue food scenarios. Our results demonstrate that shifting diets towards fish products can prevent 11-16 Mha of forest and natural vegetation conversion and reduce emissions by up to 125 MtCO2e/year compared to baseline scenarios. The study also reveals that a minimum 2.3-fold increase in fed aquaculture production above 2020 levels is necessary to meet global demand by 2050, even in low fish consumption scenarios. These findings highlight the critical role of blue foods in mitigating environmental impacts of food production and emphasize the need for integrated land-sea management approaches in global food security planning.

Introduction

Aquatic or 'blue' foods are increasingly recognized as critical for sustainable food systems that support Sustainable Development Goals (SDGs) and address climate and biodiversity challenges [1,2,3]. Greater consumption of sustainable aquatic foods can improve human health by providing key micronutrients such as omega-3 fatty acids, iron, and calcium [1,4,5]. Aquatic foods often have lower environmental footprints relative to terrestrial animal-source foods, including lower greenhouse gas emissions, water-use, and land-use [6], although this can vary depending on where and how foods are produced [7]. Aquatic foods support livelihoods for millions globally, especially in coastal and low-income regions, where they are critical for maintaining food security [8,9] as well as experiencing rising demand due to shifting income [10]. Yet, despite their important role, aquatic foods remain poorly integrated in wider food system governance, planning, and policy-relevant assessments [11]. These cross-sector dynamics underscore long-recognized sustainability trade-offs among fisheries, aquaculture, and agriculture [12].

Given important questions about how future seafood production will be realized [6] and the accelerating competition for ocean space among blue economy sectors [14,15], a thorough understanding of the implications of increased aquatic food production and consumption for society and the environment will be critical for ensuring positive outcomes across sustainability objectives. Wild-capture fisheries have plateaued in many regions, constrained by ecological limits and management challenges. While improved fisheries governance and management could yield production gains [16], the majority of future growth in aquatic food supply is expected to come from aquaculture [17]. Fed aquaculture competes with land-based animal production for resources associated with feeds [18]. Previous scenario-based estimates have suggested future shifts away from meat towards seafood could result in significant land-sparing [19] and hence reduce associated environmental costs of land-use [20]. However, consideration of economic feed-backs of aquaculture and other components of blue growth within the context of wider global food system assessments are lacking, in part due to the limited representation of aquatic foods in integrated assessment models [21,22]. More broadly, although global agricultural economic models (e.g., the OECD-FAO AGLINK-COSIMO partial-equilibrium model) have begun to incorporate fish and aquaculture, including through the OCE-FAO Outlook and linked SeaSIM modules, systematic integration of blue foods is still emerging. Recent work (e.g., [50]) demonstrates deeper AgLink-Cosimo–SeaSIM coupling, but such efforts remain exceptions rather than the norm.

Here, we present an integrated modelling framework that incorporates supply and demand for terrestrial, marine, and freshwater products, and projects future land-use and associated sustainability indicators (e.g., greenhouse emissions). We have developed a representation of the integration of fish inputs in a global land-use model, the Global Biosphere Management Model (GLOBIOM)[23] (Methods). In our approach, we first added to GLOBIOM a representation of fish production, trade and consumption, building on fisheries data from the FAO and other scientific sources. Given the ongoing rise in fed aquaculture [24], we also incorporate the dynamics of fish meal and fish oil (FMFO) production and consumption, and the increased incorporation of crops in fish feeds (hereafter: aquafeeds) [19]. We then designed scenarios to explore the effect of changing fish production and consumption dynamics on global food system indicators such as aquafeed production and crop usage, land cover, greenhouse emissions, water-use, and nitrogen use.

To explore how aquatic foods might influence future food systems, we developed three scenarios based on the Shared Socioeconomic Pathway 2 (SSP2), which assumes moderate population growth, economic development, and technological change with historical patterns continuing [26]. These

scenarios vary assumptions about diets, capture fisheries, and aquaculture expansion to reflect contrasting futures (Table 1). Because capture fisheries and non-fed aquaculture are held constant (or bounded) in all scenarios, any additional fish consumption beyond these fixed levels is met endogenously by increases in fed aquaculture production within GLOBIOM. Thus, all growth in total fish consumption is ultimately satisfied through fed aquaculture expansion. In the Business as Usual scenario, diets follow current trends, capture fisheries remain near present levels, and aquaculture grows gradually with ongoing efficiency improvements and shifts in aquafeed composition [24]. For all scenarios, we exogenously assume that the proportion of fishmeal and fish oil (FMFO) in aquafeeds declines over time (see Methods). The Blue Transformation scenario aligns with FAO's vision for sustainable seafood [17], assuming a 10% dietary shift from terrestrial livestock to fish, improved fisheries management that increases catch capacity for all stocks[51], and a maximum 50% increase in non-fed aquaculture across all countries. The Barriers to Blue Growth scenario explores a constrained future where climate and management challenges reduce capture fisheries by 10% based on projected global declines in carrying capacity by 2050[48], non-fed aquaculture remains flat, and diets shift 10% away from fish toward livestock, distributed across species according to calorific differences relative to Business As Usual (BAU).

Table 1. Scenario Dimensions

Scenario Dimension	Barriers to Blue Growth	BAU (Business As Usual)	Blue Transformation
Human Diet	10% of fish calories are **replaced with terrestrial livestock** in diets by 2050 compared to SSP2	Maintains SSP2 pathway levels - steady increase in global fish consumption, following historical growth patterns	10% of terrestrial livestock calories are **replaced with fish** in diets by 2050 compared to SSP2
Capture	Capture fisheries production decreases by 10% from 2020 levels	Capture fisheries maintain 2020 levels of production	Capture fisheries production increases by 10% from 2020 levels
Non-Fed Culture	Non-fed aquaculture production constrained to 2020 levels	Non-fed aquaculture production constrained to 2020 levels	Non-fed aquaculture production projected to increase by 50% over 2020 levels.

Results

Across all scenarios, global demand for aquatic foods increases substantially from 2000 to 2050, but the magnitude and composition of this demand vary depending on assumptions about diets, capture fisheries, and aquaculture development (Figure 1). In GLOBIOM, demand is always met by production, so these projections reflect both consumer preferences and the model's assumptions about supply-side responses. In the Blue Transformation scenario, characterized by a 10% dietary shift toward fish, improved fisheries management, and a 50% increase in non-fed aquaculture, demand rises most sharply, reaching over 274 million tonnes by 2050, a 2.7-fold increase from 2000 levels. The BAU scenario, which maintains current dietary trends and production capacities, results in a more moderate increase to 248 million tonnes. In contrast, the Barriers to Blue Growth scenario, which assumes a 10% dietary shift away from fish and declining capture fisheries, leads to the lowest demand at 224 million tonnes by 2050. These global trends mask substantial regional variation where demand trajectories differ markedly across regions such as China, Brazil, and sub-Saharan Africa (Figure S1). In particular, regions with rapidly growing populations or strong aquaculture potential show the steepest increases in demand under the Blue Transformation scenario, underscoring the importance of regional context in shaping future blue food trajectories.

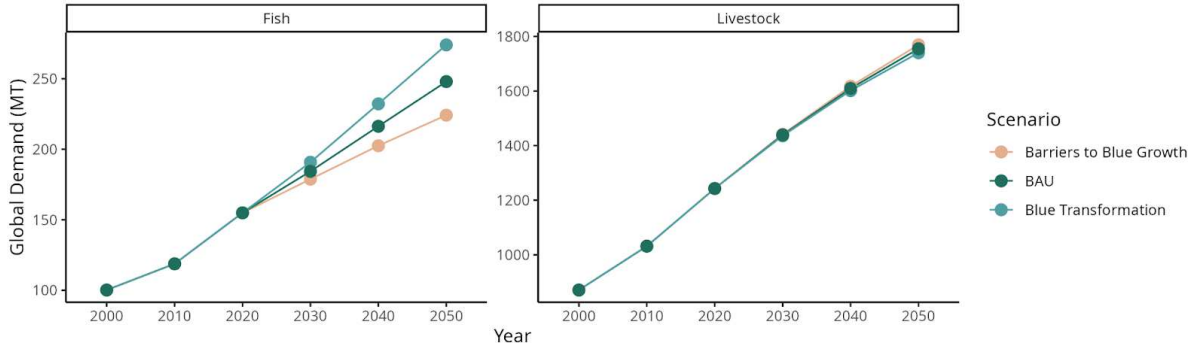


Figure 1. Projected global demand for fish and livestock from 2000 to 2050 across three scenarios: Blue Transformation, Business as Usual, and Barriers to Blue Growth. Fish demand increases most sharply under Blue Transformation due to dietary shifts and aquaculture expansion, while livestock demand continues to rise steadily across all scenarios, especially where fish consumption declines.

The Feasibility of Different Futures

By 2050, to meet the assumed levels of demand, and depending on assumed trends in wild catch, the global production of aquaculture across the scenarios we considered ranged from ca. 163 million tonnes in the BAU scenario (145 million from Fed aquaculture) to ca. 180 million tonnes in the Blue Transformation scenario (157 million from Fed aquaculture), and down to ca. 148 million tonnes in the Barriers to Blue Growth scenario (131 million from Fed aquaculture) (Figure 2b). To achieve this lowest-production scenario, would require an expansion of ca. 67 million tonnes (83%) of aquaculture above 2020 levels. Because fed-aquaculture production is endogenously controlled by demand in the model, 131 million

tonnes is the minimum amount of fed production needed to satisfy global demand by 2050 across all scenarios, which is a 128% increase in production above 2020 levels.

These levels are similar to two-fold increase estimates of total global production potential calculated using bottom-up biophysical production models [27] and are consistent with estimates of at least a six-fold increase in seafood production [28].

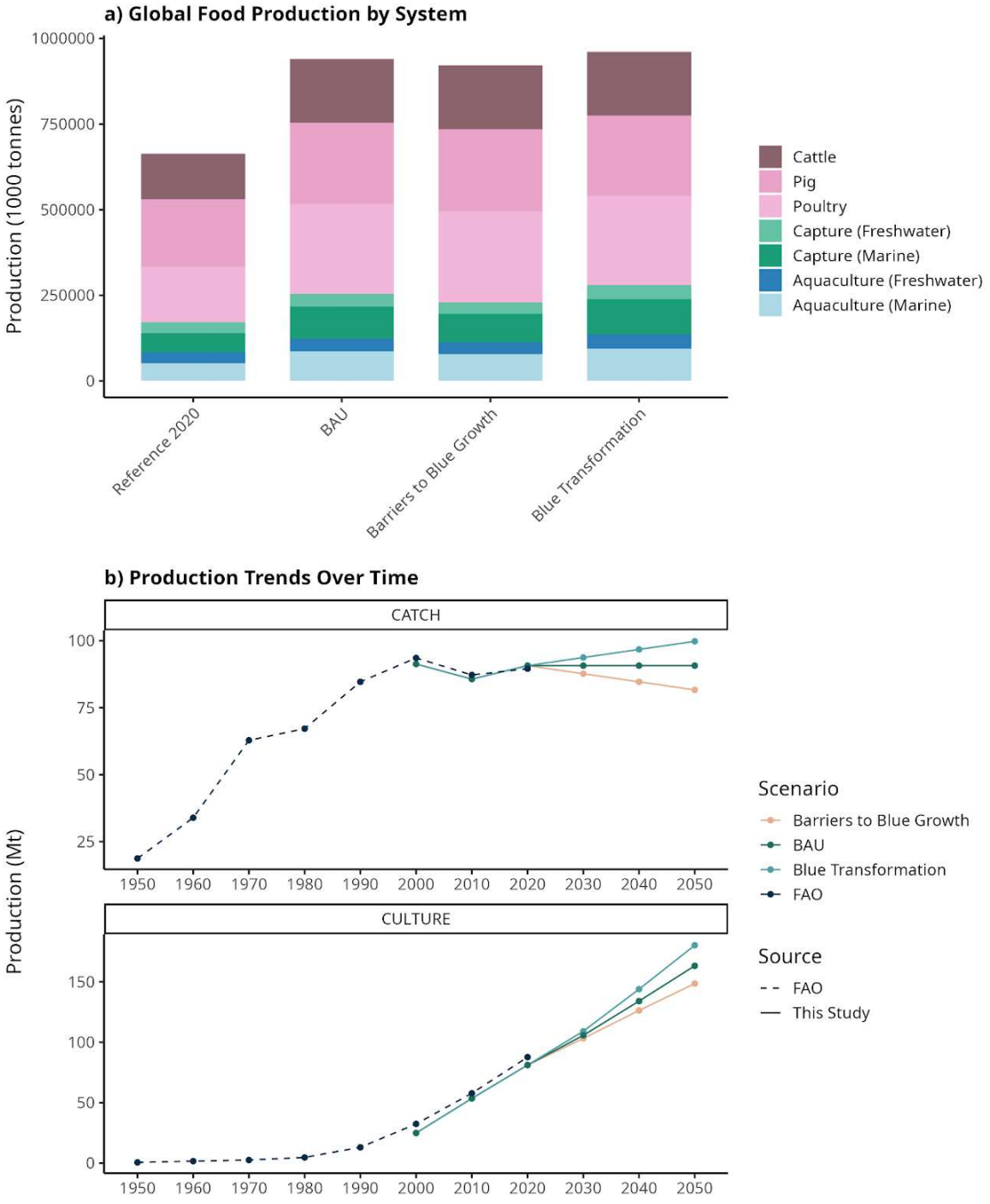


Figure 2. Global production trends and scenario comparisons for wild-capture fisheries and aquaculture from 1950 to 2050. *(a) Global food production by system is shown for four scenarios: Reference 2020, Business As Usual (BAU), Barriers to Blue Growth, and Blue Transformation. Production systems include terrestrial livestock and aquatic sources—freshwater and marine capture fisheries and aquaculture. (b) Historical production data (1950–2020) from FAO are represented by dashed gray lines in both panels. Solid colored lines show GLOBIOM model outputs from 2000 to 2050 under 18 scenarios*

that vary by dietary shifts (±10% fish consumption), aquaculture expansion (0 or +50% non-fed aquaculture), and wild-capture fisheries production changes (±10%). In the CATCH panel (top), wild-capture fisheries production increased until ~2000 and then stabilized. In the CULTURE panel (bottom), aquaculture production shows continued growth across all scenarios, with the most pronounced increases under the Blue Transformation pathway.

Global Aquafeed and Crop Usage

Aquafeed production and consumption increases across all of the scenarios we considered. However, aquafeed represents only a small fraction of total global feed crop use, which is dominated by terrestrial livestock sectors such as poultry, pigs, and cattle (Figure 2a, 3a). By 2050, the vast majority of these feeds are composed of terrestrial crops (Figure 3b), as the inclusion of fish meal and fish oil is expected to decrease over the next few decades (Figure S2)[54,55]. In the Blue Transformation scenario, total global aquafeed requirements reach 193 million tonnes, representing a 114% increase from 2020 levels (90 million tonnes). In contrast, the Barriers to Blue Growth scenario sees aquafeed requirements rise to 162 million tonnes, a more modest 79% increase. The BAU scenario falls in between, with production reaching 180 million tonnes, nearly doubling 2020 levels. Despite these differences in consumption, the relative use of terrestrial crops remains fairly consistent across scenarios, and aquafeed demand remains relatively insensitive to scenario assumptions due to its small share in overall feed crop use.

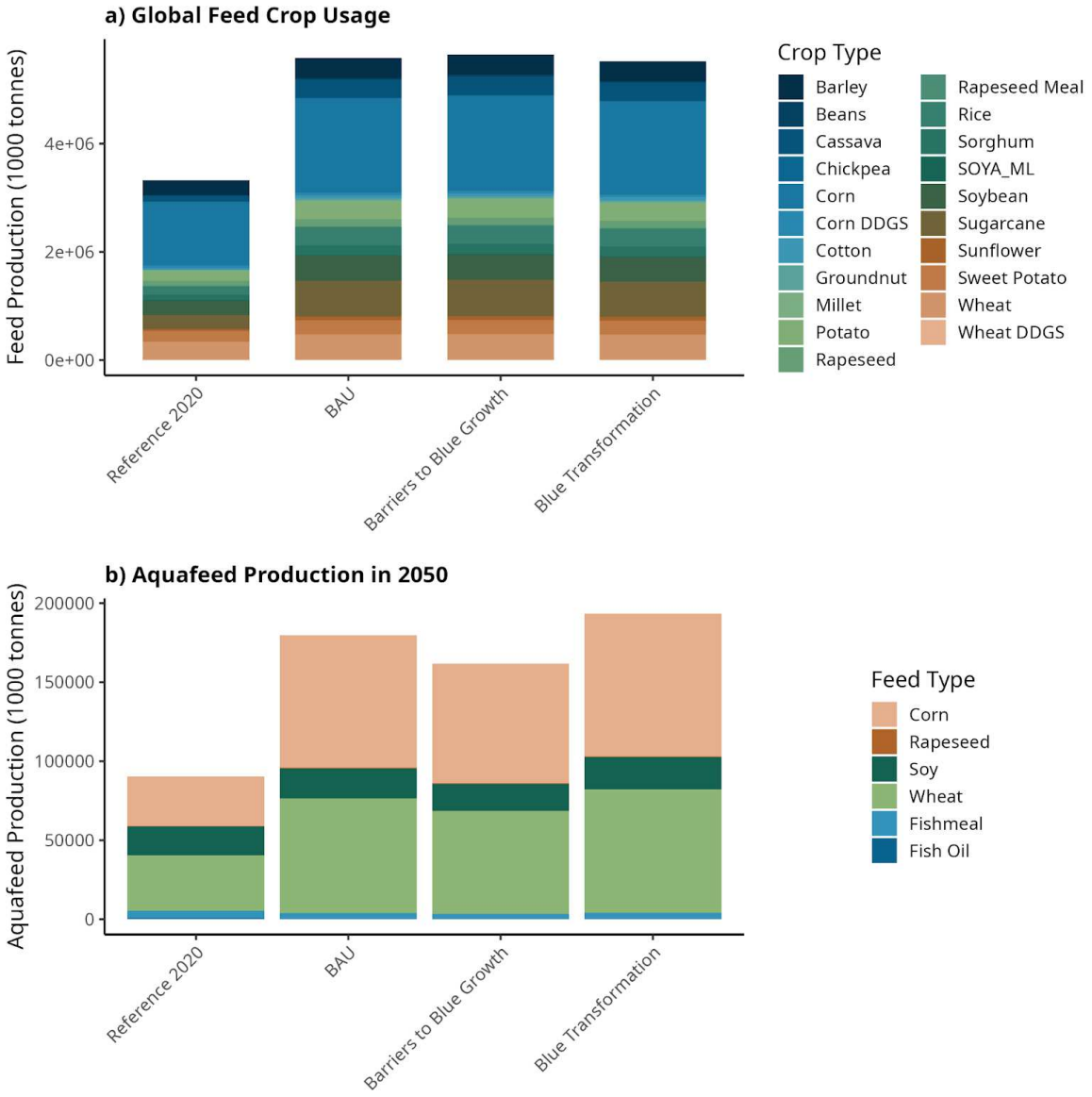


Figure 3. Global feed crop usage and aquafeed production under four future scenarios. *(a) Total global feed crop usage (in thousand tonnes) is shown for Reference 2020, Business As Usual (BAU), Barriers to Blue Growth, and Blue Transformation scenarios. Feed crops include a wide range of types such as cereals (e.g., corn, barley, wheat), legumes (e.g., soybeans, chickpeas), root crops (e.g., cassava, potatoes), and oilseeds (e.g., rapeseed, sunflower), among others.(b) Aquafeed production in 2050 is broken down by feed type across the same four scenarios. Key feed ingredients include corn, rapeseed, soybean meal/cake, and wheat by-products.*

Blue Foods can reduce terrestrial environmental pressures

Here we show the influence of each scenario on global sustainability indicators (Figure 4). We compare each scenario to the Business-as-Usual scenario, and find substantial, sometimes counterintuitive differences across the four dimensions of land-use sustainability. Notably, shifts in diets towards fish products and away from livestock products can prevent 11 - 16 Mha of forest and natural vegetation from being converted to pasture or cropland. Whereas, in the opposing set of scenarios where livestock products are substituted for fish products, we can expect 9 - 12 Mha of additional natural lands to be placed under crop or livestock production. Within each diet scenario, different assumptions

about aquaculture production lead to varying projected changes in land-use, with increases in wild-capture generally leading to less need to convert natural lands to human-managed production.

The differences in emissions from the baseline scenario follow these trends in land-use. Shifting human diets towards fish leads to up to 125 MtCO2e reduction in emissions from livestock production, crop production and land-use change. Whereas increased emissions of ca. 71 Mt CO2e/year are projected to occur from shifting diets towards livestock products. This finding is broadly consistent with previous work that shows the relative environmental costs of land-based meat production [7], although we do not calculate the GHG emissions of fish production here.

Differences in water and nitrogenous fertilizer use are more diverse but follow similar patterns as savings in land cover and emissions. Across the scenarios, water use varies by ~25 km^3, and nitrogenous fertilizer use varies by ~ 4 million Tonnes. The most notable ways to reduce use of these resources are through either shifts in diet or expansions of non-fed aquaculture. However, water and nitrogen use seem to be particularly sensitive to changes in wild-capture in our model, which may be related to the availability of FMFO derived from wild capture that enables fed aquaculture.

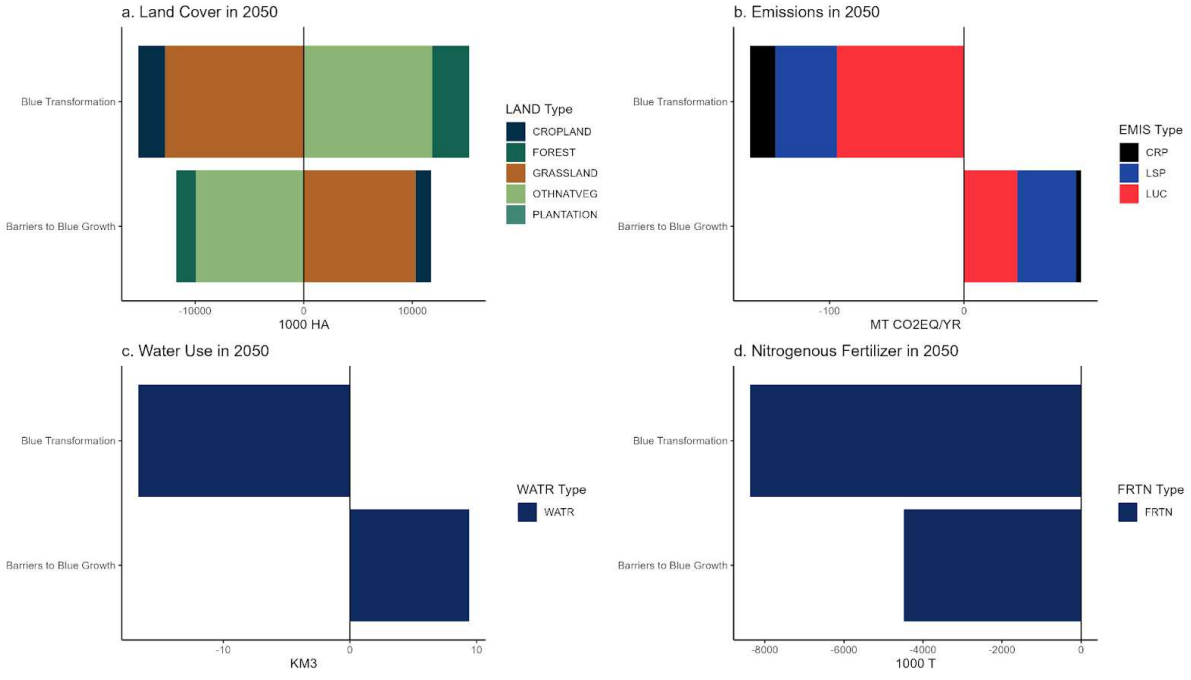


Figure 4. Environmental Impacts of Land-Use sustainability. Impacts of Changing Fish Production and Consumption Dynamics on Global Sustainability Indicators in 2050, compared to the baseline scenario, (Diet 0 | Non-Fed 0 | Capture 0). (a) Difference from the baseline scenario of land use categories (cropland, forest, grassland, other natural vegetation, plantation) measured in 1000 hectares (HA). (b) Difference from the baseline scenario of greenhouse gas emissions from different sources (crop production, livestock production, land use change) measured in million tonnes of CO2 equivalent per year (MT CO2EQ/YR). (c) Difference from the baseline scenario of water consumption measured in cubic kilometers (KM3). (d) Difference from the baseline scenario of nitrogenous fertilizer application measured in 1000 tonnes (T). The scenarios are combinations of different assumptions about diet (±10% fish consumption), non-fed aquaculture production (0 or +50% increase in non-fed aquaculture), and wild capture fisheries (±10% production).

Distribution of Terrestrial Influence

The impacts of each scenario would not be felt uniformly across the globe. Figure 5 illustrates the regional differences in cultivated lands, natural lands, and fish production between two scenarios (Barriers to Blue Growth and Blue Transformation) compared to the BAU scenario in 2050. For cultivated lands (Figure 5a), the Barriers to Blue Growth scenario shows an increase in South America (200-300 thousand ha), while parts of Asia and Australia show decreases. Conversely, in the Blue Transformation scenario, South America, particularly Brazil, shows a substantial decrease in cultivated lands (300-400 thousand ha), while parts of Asia, especially China, show increases. This suggests that increasing fish consumption leads to a reduction in land used for agriculture in South America, likely due to decreased demand for land-intensive livestock farming. These regional responses also reflect the fact that aquafeed crop demand can influence land use in distant regions through global trade and market linkages resolved within GLOBIOM, meaning that shifts in fish consumption in one part of the world can generate land-use impacts elsewhere. The impact on natural lands (Figure 5b) correlates with changes in cultivated lands. However, decreases in cultivated land do not always translate proportionally into gains in natural land in GLOBIOM, because land released from agriculture does not necessarily revert to the specific "natural land" categories reported here within the same time step or under regional land-use constraints.

In Barriers to Blue Growth, South America shows a significant loss of natural lands (100-150 thousand ha). However, in Blue Transformation, there is a notable increase in natural lands in South America (300-400 thousand ha) and parts of Africa and Southeast Asia. This indicates that increasing fish consumption helps preserve natural lands, particularly in biodiversity-rich regions. When diets shift away from blue foods in Barriers to Blue Growth, most regions show a decrease in fish production, with South America experiencing the largest decrease (8,000-10,000 thousand tonnes). In contrast, Blue Transformation shows a substantial increase in fish production across many regions, particularly in China, South America, and parts of Africa (6,000-8,000 thousand tonnes). This demonstrates that increasing fish in diets leads to a significant boost in global fish production, with China playing a major role in meeting this increased demand.

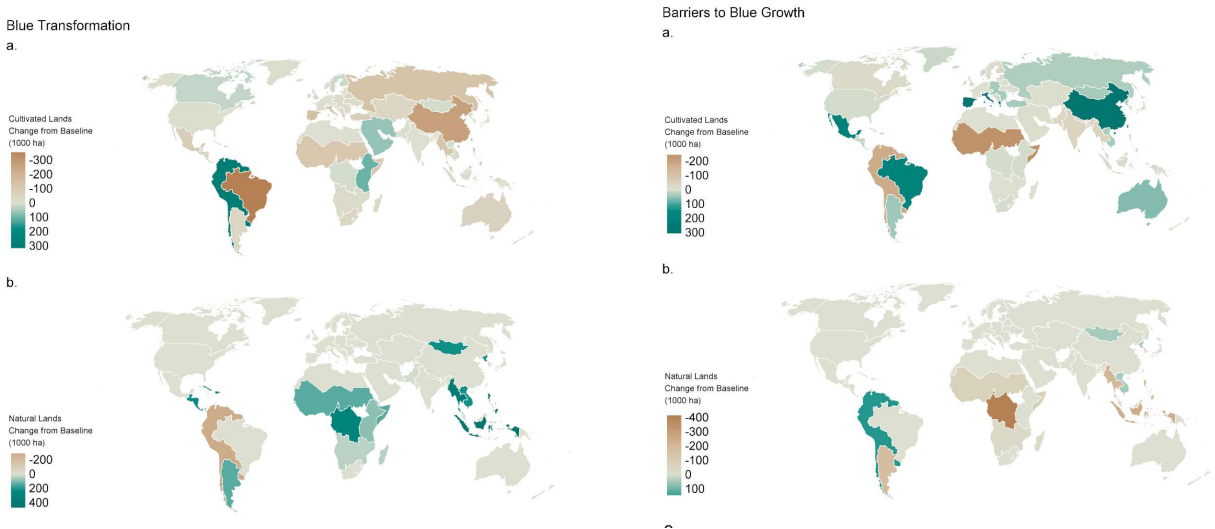


Figure 5. Regional differences in (a) cultivated land area (1000 ha), (b) natural land area (1000 ha), and (c) fish production (1000 T) in 2050 relative to the Business-as-Usual scenario. Left panels: Blue Transformation scenario, showing greater natural land preservation and increased fish production in key regions. Right panels: Barriers to Blue Growth scenario, showing expanded cultivated lands and reduced fish production. Blue shades indicate increases; orange shades indicate decreases compared to baseline.

Discussion

This analysis provides a first step towards building an integrated assessment that spans terrestrial and aquatic food systems. Our findings highlight the need for more ambitious expansion of aquaculture under these scenarios than previously documented in existing literature. One of the key objectives of the FAO's vision for transforming aquatic food systems is to achieve sustainable aquaculture that equitably satisfies global demand for aquatic foods. While the FAO suggests a 35% expansion in sustainable aquaculture production is needed to meet this objective by 2030 [17], our scenario analysis indicates a requirement of 35-39% expansion in fed aquaculture to meet future demands by 2030. Importantly, by integrating fish into global Integrated Assessment Models (IAMs), we are able to assess the range of land-based environmental benefits associated with a blue transformation across multiple countries. This approach provides advantages over static life-cycle assessment (LCA) methods, which quantify average impacts per tonne of product under present-day conditions. In contrast, GLOBIOM captures dynamic, marginal effects that arise as land-use, yields, diets, and trade evolve over time. For example, the marginal land-use impact of 1 tonne of soy in 2050 can differ substantially from today because the entire background landscape and market context has changed — a feature static LCA cannot represent. Our approach also allows, in principle, for sensitivity analyses on multiple assumptions (e.g., alternative aquafeed compositions), highlighting how integrated assessment frameworks can evaluate systemic responses that LCA cannot address.

As demonstrated in our results, variations in some aspects of the global fish production and consumption sector can have important implications for land-use, whereas other aspects have more modest impacts. Substituting fish for terrestrial livestock products, even at a relatively modest rate of 10%, has much higher implications than the other potential interventions that we explored here. Similarly, we show that at a global scale, fish production and consumption plays an important role in mitigating the growth of more resource intensive animal agriculture. The distribution of impacts and production requirements in a world of higher fish production and consumption reflect the high level of globalization in the fish production sector [29]. Increasing fish consumption leads to higher crop production in some regions, increased fish production in others, and environmental savings in still others.

Our scenarios are necessarily simplified, and greater barriers may exist to achieving Blue Transformation that have not been considered here, including trade dynamics and both rapid and long-term climate impacts. These factors could be developed further in our framework. Whilst FAO data is currently widely used for analyses like these, there are reasons to be skeptical about the exact values [30], especially in inland systems where freshwater fish catch is thought to be underreported by 65 – 70% [31]. Coupling a partial equilibrium economic model with models of fish production based on biophysical data to predict production capacities will allow for more refined estimates of future supply [32] and also allow more sophisticated analyses that can evaluate climate implications in marine food systems [33,34]. Incorporating biophysical elements into modelling fish production may also allow for better understanding of how and where marine production influences the nutrient security of nations [35]. Further biophysical coupling would allow better integration with climate-related impacts on fish stocks and comparison with other studies looking at the change in fish production under climate change [19,36,37,38,39]

We focus on land-based environmental impacts and pressures; further GLOBIOM developments would integrate the environmental consequences of spatial re-allocation and changes in marine fisheries and aquaculture on marine and freshwater environments. This integration would include

agricultural impacts such as nutrient runoff and its effects on aquatic ecosystems. Currently, prices for fish products are gleaned from the FAO dataset on trade in fish products. However, the costs of the various processes incorporated in the model (reduction to FMFO, processing to remove trimmings, production across different cultivation and capture types) are not well-defined. Improving these numbers via a review of the scientific and grey literature would enable an improved understanding of how these different processes might be favoured or disregarded under different economic conditions. Adding a more spatial understanding of production systems would also give a better sense of the spatial requirements of aquaculture systems so that questions of marine spatial planning and land-use change from aquaculture ponds/facilities could be addressed. Recent advances in environmental footprint and biodiversity impacts of food and feeds could be integrated from emerging research [7,40,41].

Changes in competition for feed resources across marine-terrestrial fed animals in future are an important consideration. Strengthening the representation of known links between terrestrial and marine production would allow better insights into linked challenges. This would include obtaining a more comprehensive and regionally-disaggregated understanding of crop inputs into aquafeeds. It would also include incorporating the flow of seafood products into terrestrial livestock feeds, which is currently not modelled in GLOBIOM. In some regions, additional production systems could be modelled, such as combined freshwater rice farms with finfish production common in southeast Asia.

The extended framework could be used to assess mitigation scenarios to reduce climate (GHG and biodiversity) impacts in future, and to help address questions related to the nexus of biodiversity, climate, food and water (IPBES). The need for future analyses that integrate estimates between land and sea cannot be overstated. This is particularly critical as much demand is expected to come from China, where mariculture and freshwater aquaculture are suspected to be at biophysical capacity in many areas [42]. We do not fully capture the environmental impacts of producing fish at sea or in cultivations on land. This may affect decisions around the design of food systems built on fish products as not all fish products are equal in terms of environmental and greenhouse gas impact – from a greenhouse gas perspective, some fish and shellfish are just as benign as plants while others are as environmentally impactful as terrestrial meats [6,43]. The environmental impacts of mariculture specifically can vary widely depending on species, production methods, and management practices, with potential effects ranging from nutrient pollution to habitat modification (Garlock et al., 2024). Incorporating estimates of these environmental impacts may even allow for analyses that explore the optimal distribution of production between the land and sea for certain sustainability indicators, like carbon emissions, and land/sea use change. Such analyses would allow for minimizing the environmental costs of production whilst also providing for the demands of human populations at the global and regional scales and thus would inform planning for future production.

Methods

We use the partial equilibrium model, Global Biosphere Management model (GLOBIOM) [44], which is implemented in the General Algebraic Modeling System, GAMS [49], to estimate future global land-use and impacts. To incorporate fisheries and aquaculture dynamics, we developed a 'fish module' within the GLOBIOM framework as depicted in Figure 6. We developed four datasets using R (Ihaka and Gentleman, 1996) for including global fish products and dynamics into GLOBIOM: fish production, demand for fish products, rates of fish processing, and aquafeeds for fed fish production systems.

Based on the availability of reliable data for these four types of parameters, we consider ten major groups of fish products that are used for either food or livestock feed in our analysis (Table S2). These include all major types of finfish, bivalves, and cephalopods, whilst excluding marine mammals, seaweeds, and other marine products such as sponges and echinoderms.

The fish module and its component products and demand (Figure 6) are incorporated by GLOBIOM similarly to already present terrestrial commodities. Additionally, we link terrestrial and fish production via the demand for terrestrial-based crops that are incorporated into aquafeeds for fish aquaculture production. We make generic assumptions about costs for each type of fish production, as well as processing fish products into one of their derivatives, such as fish meal, oil, and waste. These costs then influence the algorithm that seeks to optimise the consumer and producer surplus. We also assume that trade in fish products occurs between each GLOBIOM region, however because of the lack of reliable global data on bilateral trade in fish products, we implement trade 'unilaterally' whereby each region exports/imports from and to a homogenized global market.

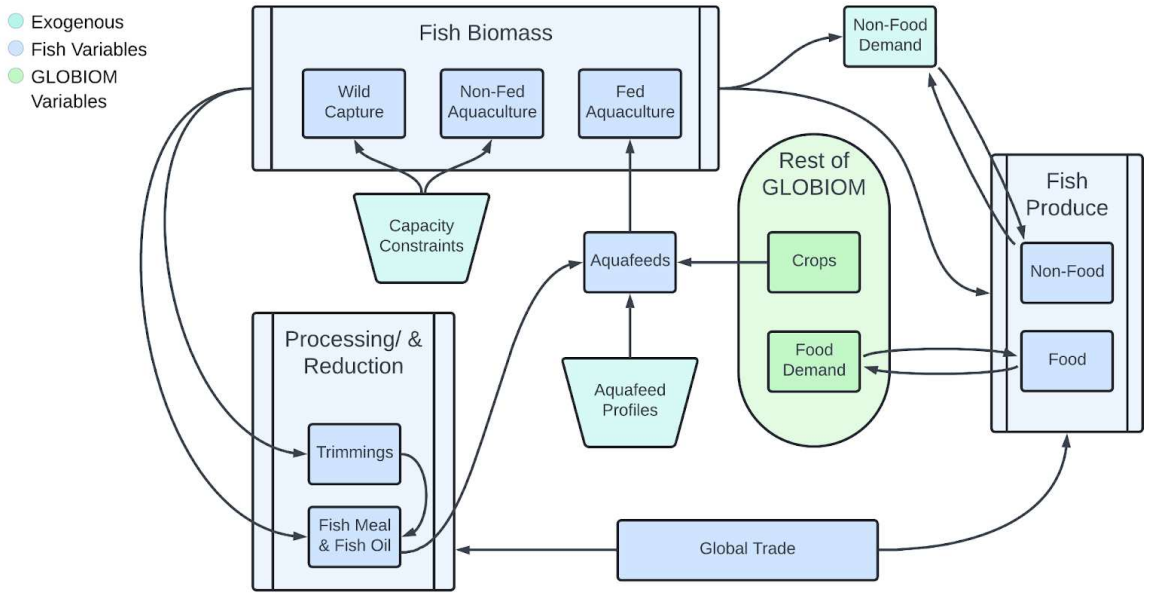


Figure 6. Structure of data processing for integrating fish inputs into GLOBIOM. *The diagram illustrates how fish biomass from wild capture, non-fed aquaculture, and fed aquaculture enters the modeling framework. Capacity constraints and processing steps (including trimmings and conversion to fish meal and fish oil) feed into aquafeed profiles, which link to crop demand and other components of GLOBIOM. Arrows indicate flows between fish production systems, aquafeed formulation, global trade, and final food and non-food uses.*

For each of these datasets, we harmonize the values for the base year 2000, which GLOBIOM uses for initialization.

Harmonizing Historical Supply and Demand

Our analysis uses FAO data, from 2000 – 2019, as the basis for estimating global and regional fish supply and demand. For supply we use the dataset 'Global production by production source Quantity (1950 – 2020)' and for demand we use the Food Balance databases. The supply dataset reports the production of each type of fish disaggregated by

country, production type (aquaculture vs. wild capture), environment (marine, brackish or freshwater), and FAO Fishery Region. The demand dataset reports disaggregated demand for fish products, including demand for food, feed, other uses, and exports. It also reports local supply from production, imports, and 'stock variation'. Because these values are reported for fish products at a higher level of aggregation than the supply dataset, we disaggregated the fish products using a supplementary dataset from the International Food Policy Research Institute (IFPRI) to match the supply dataset. We also use the ' Global fish trade - All partners aggregated' database and the 'Global Fish Processed Products Production Statistics' to quantify the flow of trade and rate of processing of each fish product. As these datasets contain inconsistencies in the demand and supply balance on both global and regional scales, we perform several data transformations to create a dataset that is balanced both locally and globally for all of the fish types of interest (For full details see Supplement 2).

We addressed two types of inconsistencies:

1. **Discrepancies in production amounts**: When disagreement between the amount of production for a given fish type, region, and year occurred between the amount of production for a given fish type, region, and year, we selected the production value that most closely balanced the remaining supply and demand elements (i.e., production + imports – (Food + Feed + Other + Exports) = 0). Where this did not fully resolve the discrepancy, we scaled the elements of the non-chosen dataset to match the chosen production value.
2. **Missing production values:** In cases where production values existed in one dataset but were missing in the other, we imputed values based on averages from similar datapoints. Our imputation process followed this hierarchy:

    a) Calculate average demand values from 2000-2019.

    b) If unavailable, use the average aggregated demand values for other fish types within the same country for that year.

    c) If still unavailable, use average global demand values for that fish type.

Estimating Future Demand

Using our balanced supply and demand dataset from 2000 – 2019 we processed each discrete production or demand type (e.g. Salmon produced by mariculture in the Atlantic, Northeast or salmon consumed as food in the Argentina Region) and we applied a rolling mean across a 7 year window to dampen variation and then fit a general additive model (gam) using the R package mgcv [56].

For wild capture marine fisheries, which are projected to remain stable from 1990- 2030 at the global scale [24], we took the average production for each country, fishery region and fish commodity group across the years 2000-2019 as the upper limit to supply, 'capacity', that GLOBIOM can produce. We then use these values to force supply capacity constraints and demand quantities for the years 2000, 2010, and 2020 (where we use 2019 values for 2020).

In the BAU assumptions, for future years (2030, 2040, and 2050), demand quantities are calculated endogenously by GLOBIOM for each commodity according to SSP2 population and consumption patterns on a regional level, and then balanced against supply to result in a realized demand for goods. Supply constraints for fed, nonfed, and wild-capture fisheries are imposed as upper-bounds on production and are calculated. We used these projections of supply as production 'capacities' which we set as exogenous upper bounds on the amount of production that a given production system can generate during GLOBIOM's optimization. We calculate future capacities, ***C'***, using 2020 as the baseline year (**C**) according to the linear equation (Equation 1), so that by the target year, ***T = 2050***, the change in capacity reflects the scenario assumption, ***s***.

$$C'(t) = (1 + \frac{t-2020}{T-2020} \times s) \times C \qquad \text{Equation 1}$$

We incorporate non-food demand, however, because it represents a small fraction of total consumption, we do not implement the full economic model as described above. Instead, we use the results of the smoothing functions described above, to project this 'other demand' to 2050, and add this demand for products to the total demand that GLOBIOM calculates.

In addition to demand quantities for each fish product in a given region, we use own-price commodity elasticities from IFPRI and use them to calculate fish market prices based on FAO trade data for the year 2000. For prices, for those commodities that are 'unprocessed' (i.e. that do not contain key words in the product description such as 'FILLET, MEAT, PREP, SAUCE, or STICK') we scale the reported value by removing the proportion of waste described in Table 2. To calculate price for a given fish product, we then aggregated the quantity and value of each for the time period 1997 – 2003 and divided value by quantity. These elasticity and price values are then used as inputs for GLOBIOM to balance supply and demand.

We calibrated production and demand quantities by modifying the costs of fish production for each system (catch, fed aquaculture, nonfed aquaculture) that GLOBIOM uses to maximize consumer and producer surplus. This allowed us to tune the amount of production of fed aquaculture to match FAO data.

Fish Processing Rates

Like livestock products, only a portion of landed fish weights make their way onto consumers plates to meet food demand, and much of the fish biomass used as feed in aquaculture and livestock systems has been reduced to fish meal or fish oil. Because FAO reports fish quantities in 'live-weight', we distinguished between the quantity of 'final' biomass that could be used to meet actual food and feed demand, and calculate the quantity of fish waste biomass that could be used as inputs to FMFO production. We used estimates of waste to 'final' (filets, steaks, etc.) biomass from [45,46] (Table 1).

Table 2. Assumed proportion of waste from processing live-weight fish. Estimates for cephalopods from Koueta et al. (2014)[46], waste proportions of finfish, shrimp, other crustaceans, and other molluscs are taken from James et al. (2011)[45].

Fish Type	Proportion of Waste
Finfish	0.5
Shrimp	0.4
Other Crustaceans	0.7
Cephalopods	0.35
Other Molluscs	0.7

We use reduction ratios reported by Peron et al (2010)[47] and assume that, for all fish types, the amount of fish meal produced from a unit of live weight fish will be 0.225 the initial biomass, and the amount of fish oil will be 0.04. They argue that, all things being equal, reduction ratios should be stable over time, with minimal room for technological improvements, and deviations from these ratios (which are derived at the country level) are likely due to the addition of non-FMFO target species, or the deviation of FMFO-target species to food consumption [47]. We assumed that these same ratios hold for the reduction of fish waste biomass to FMFO. We use FAO reports of FMFO production to limit the regions that can reduce fish biomass to FMFO in the years 2000-2020, and then allow all regions to produce FMFO in future projected years. We also assume that the sources of reduction, globally, is composed primarily of pelagic species in 2000 – 2020, and then shifts to using more waste biomass by mid-century[57,58] (Figure 7).

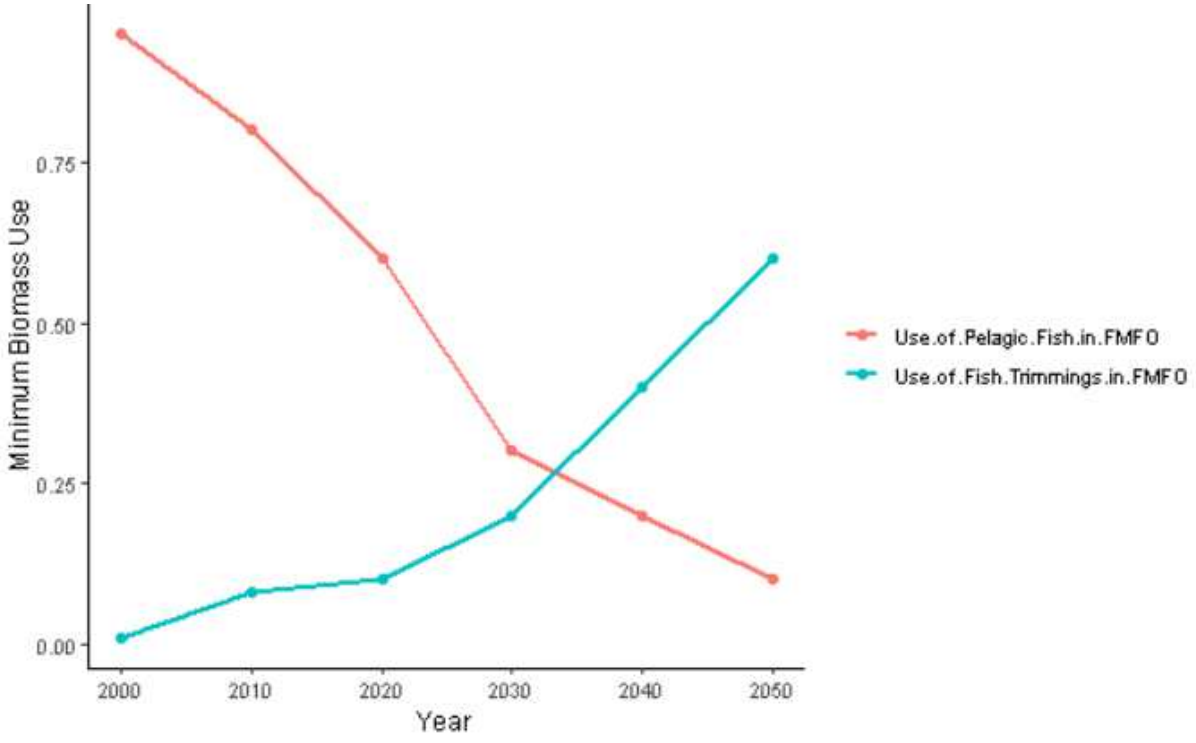


Figure 7. Projected shift in sources of fish meal and fish oil (FMFO) used in aquafeeds (2000–2050). *The red line shows the declining proportion of FMFO derived from whole pelagic fish, while the blue line indicates the increasing share from fish*

processing trimmings. By mid-century, trimmings are assumed to become the dominant source, reflecting industry trends toward reducing reliance on whole fish and improving resource efficiency in aquaculture feed production.

Estimating Aquafeed Usage in Aquaculture

Whilst novel feeds for farmed fish are under active development [40], currently the vast majority of fish feeds incorporate FMFO derived from either wild caught fishes, or from waste by-products of food fishes[53]. We modelled these dynamics and fish-feed requirements explicitly (Figure 1).

We estimated the current and future feed requirements of fish produced in aquaculture and mariculture systems by integrating data on current and projected FMFO requirements (as proportions of aquafeed), terrestrial crop proportions, proportions of fish cultivated using feeds, and estimates of feed conversion ratios (FCRs). We used estimates of FMFO proportional inclusion for fed aquaculture projected to 2020 sourced from[54]. For FCRs and the proportion of fish requiring aquafeeds we used estimates and projections out to 2025 from[55]. For all three sets of parameters, we fit general-additive models for each species group and project values for each decadal time-step to 2050. For aquafeed requirements sourced from terrestrial crops, we used estimates from [19] which already provided estimates for crop inclusion from 2015 and 2050. For the intervening decadal times steps we fit a linear regression for each country and feed type. We assumed that the proportions derived from [19] make up the non-FMFO portion of feed and that as FCRs change over time differing input quantities are needed to produce a unit of fish (Figure S5).

References

1. Crona, B. I., Wassénius, E., Jonell, M., Koehn, J. Z., Short, R., Tigchelaar, M., Daw, M.T., Golden, C.D., Gephart, J.A., Allison, E.H., Bush, S.R. Cao, L., Cheung, W.W.L., DeClerck, F., Fanzo, J., Gelcich, S., Kishore, A., Halpern, B.S., Hicks, C.C., Leape, J.P., Little, D.C., Micheli, F., Naylor, R.L., Phillips, M., Selig, E.R., Springmann, M., Sumaila, U.R., Troell, M., Thilsted, S.H., Wabnitz, C. C., 2023. Four ways blue foods can help achieve food system ambitions across nations. Nature 616, 104-112. https://doi.org/10.1038/s41586-023-05737-x
2. Halpern, B. S., Cottrell, R. S., Blanchard, J. L., Bouwman, L., Froehlich, H. E., Gephart, J. A., Sand J.N., Kuempel, C.D., McIntyre, P.B., Metian, M., Moran, D.D., Nash, K.L., Többen, J., Williams, D. R, 2019. Opinion: Putting all foods on the same table: achieving sustainable food systems requires full accounting. Proceedings of the National Academy of Sciences 116, https://doi.org/18152-18156.10.1073/pnas.2011873117
3. Roos, N., 2023. Blue foods brought to the table to improve fish-policy decisions. Nature 616, 42-43.https://doi.org/10.1038/d41586-023-00851-2
4. Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., Matthey, H., Eurich, J.G., Gephart, J.A., Fluet-Chouinard, E., Nyboer, E.A., Lynch, A.J., Kjellevold, M., Bromage, S., Charlebois, P., Barange, M., Vannuccini, S., Cao, L., Kleisner, K.M., Rimm, E.B., Danaei, G., DeSisto, G., Kelahan, H., Fiorella, K.J., Little, D.C., Allison, E.H., Fanzo, J., Thilsted, S. H., 2021. Aquatic foods to nourish nations. Nature 598, 315-320. https://doi.org/10.1038/s41586-021-03917-1
5. Hicks, C. C., Cohen, P. J., Graham, N. A., Nash, K. L., Allison, E. H., D'Lima, C., Mills, D.J., Roscher, M., Thilsted, S.H., Thorne-Lyman, A.L., MacNeil, M. A., 2019. Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574, 95-98. https://doi.org/10.1038/s41586-019-1592-6
6. Gephart, Jessica A., Golden, C.D., Asche, F., Belton, B., Brugere, C., Froehlich, H.E., Fry, J.P., Halpern, B.S., Hicks, C.C., Jones, R.C., Klinger, D.H., Little, D.C., McCauley, D.J., Thilsted, S.H., Troell, M., Allison,

E.H., 2021. Scenarios for Global Aquaculture and Its Role in Human Nutrition. Reviews in Fisheries Science & Aquaculture 29, 122–138. https://doi.org/10.1080/23308249.2020.1782342
7. Halpern, B.S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J.L., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., 2022. The environmental footprint of global food production. Nature Sustainability 1–13.
8. Cojocaru, A.L., Liu, Y., Smith, M.D., Akpalu, W., Chávez, C., Dey, M.M., Dresdner, J., Kahui, V., Pincinato, R.B.M., Tran, N., 2022. The "Seafood" System: Aquatic Foods, Food Security, and the Global South. Review of Environmental Economics and Policy 16, 306–326. https://doi.org/10.1086/721032
9. Stetkiewicz, S., Norman, R.A., Allison, E.H., Andrew, N.L., Ara, G., Banner-Stevens, G., Belton, B., Beveridge, M., Bogard, J.R., Bush, S.R., Coffee, P., Crumlish, M., Edwards, P., Eltholth, M., Falconer, L., Ferreira, J.G., Garrett, A., Gatward, I., Islam, F.U., Kaminski, A.M., Kjellevold, M., Kruijssen, F., Leschen, W., Mamun, A.-A., McAdam, B., Newton, R., Krogh-Poulsen, B., Pounds, A., Richardson, B., Roos, N., Röös, E., Schapper, A., Spence-McConnell, T., Suri, S.K., Thilsted, S.H., Thompson, K.D., Tlusty, M.F., Troell, M.F., Vignola, R., Young, J.A., Zhang, W., Little, D.C., 2022. Seafood in Food Security: A Call for Bridging the Terrestrial-Aquatic Divide. Front. Sustain. Food Syst. 5, 703152. https://doi.org/10.3389/fsufs.2021.703152
10. Naylor, R.L., Kishore, A., Sumaila, U.R., Issifu, I., Hunter, B.P., Belton, B., Bush, S.R., Cao, L., Gelcich, S., Gephart, J.A., Golden, C.D., Jonell, M., Koehn, J.Z., Little, D.C., Thilsted, S.H., Tigchelaar, M., Crona, B., 2021. Blue food demand across geographic and temporal scales. Nat Commun 12, 5413. https://doi.org/10.1038/s41467-021-25516-4
11. Tigchelaar, M., Leape, J., Micheli, F., Allison, E.H., Basurto, X., Bennett, A., Bush, S.R., Cao, L., Cheung, W.W.L., Crona, B., DeClerck, F., Fanzo, J., Gelcich, S., Gephart, J.A., Golden, C.D., Halpern, B.S., Hicks, C.C., Jonell, M., Kishore, A., Koehn, J.Z., Little, D.C., Naylor, R.L., Phillips, M.J., Selig, E.R., Short, R.E., Sumaila, U.R., Thilsted, S.H., Troell, M., Wabnitz, C.C.C., 2022. The vital roles of blue foods in the global food system. Global Food Security 33, 100637. https://doi.org/10.1016/j.gfs.2022.100637
12. Blanchard, J.L., Watson, R.A., Fulton, E.A., Cottrell, R.S., Nash, K.L., Bryndum-Buchholz, A., Büchner, M., Carozza, D.A., Cheung, W.W.L., Elliott, J., Davidson, L.N.K., Dulvy, N.K., Dunne, J.P., Eddy, T.D., Galbraith, E., Lotze, H.K., Maury, O., Müller, C., Tittensor, D.P., Jennings, S., 2017. Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. Nat Ecol Evol 1, 1240–1249. https://doi.org/10.1038/s41559-017-0258-8
13. Gephart, J A, Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W.B., Ziegler, F., Troell, M., 2021. Environmental performance of blue foods. Nature 597, 360-+. https://doi.org/10.1038/s41586-021-03889-2
14. Farmery, A. K., Allison, E. H., Andrew, N. L., Troell, M., Voyer, M., Campbell, B., Eriksson, H., Fabinyi, M., Song, A.M., Steenbergen, D. ,2021. Blind spots in visions of a "blue economy" could undermine the ocean's contribution to eliminating hunger and malnutrition. One Earth 4, 28-38. https://doi.org/10.1016/j.oneear.2020.12.002
15. Jouffray, J.-B., Blasiak, R., Norström, A.V., Österblom, H., Nyström, M., 2020. The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. One Earth 2, 43–54. https://doi.org/10.1016/j.oneear.2019.12.016
16. Costello, C., Cao, L., Gelcich, S. et al. The future of food from the sea. Nature 588, 95–100 (2020). https://doi.org/10.1038/s41586-020-2616-y
17. FAO, 2022. Blue Transformation - Roadmap 2022–2030: A vision for FAO's work on aquatic food systems. Rome. https://doi.org/10.4060/cc0459en.
18. Cottrell, R. S., Fleming, A., Fulton, E. A., Nash, K. L., Watson, R. A., Blanchard, J. L., 2018. Considering land–sea interactions and trade-offs for food and biodiversity. Global Change Biology 24, 580-596. https://doi.org/10.1111/gcb.13873

19. Froehlich, H.E., Runge, C.A., Gentry, R.R., Gaines, S.D., Halpern, B.S., 2018. Comparative terrestrial feed and land use of an aquaculture-dominant world. Proc. Natl. Acad. Sci. U.S.A. 115, 5295–5300. https://doi.org/10.1073/pnas.1801692115
20. Xia,S., Takakura ,J., Wu, W., Blanchard, J.L., Heneghan, R.F., Yamakawa, T.,i Tsuchiya,K., Hasegawa, T., Fujimori, S., Takahashi,K. (2023) Potential environmental and nutritional benefits of replacing ruminant meat with forage fish,Sustainable Production and Consumption 40, 265-276. https://doi.org/10.1016/j.spc.2023.07.005.
21. Harfoot, M., Tittensor, D. P., Newbold, T., McInerny, G., Smith, M. J., & Scharlemann, J. P. (2013). Integrated assessment models for ecologists: the present and the future. Global Ecology and Biogeography, 23(2), 124-143.
22. Salin,M., Kedward,K., & Dunz, N. (2024). Assessing Integrated Assessment Models for Building Global Nature-Economy Scenarios. Working Paper #959. Banque de France. Available on publications.banque-france.fr/en
23. Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S.D., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. https://doi.org/10.1016/j.enpol.2010.03.030
24. FAO, 2024. The State of World Fisheries and Aquaculture (SOFIA): Blue Transformation in Action. Food and Agriculture Organization, Rome.
25. Froehlich, H. E., Gentry, R. R., & Halpern, B. S. (2018). Global change in marine aquaculture production potential under climate change. Nature ecology & evolution, 2(11), 1745-1750.
26. O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., Van Ruijven, B.J., Van Vuuren, D.P., Birkmann, J., Kok, K., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global environmental change 42, 169–180.
27. Fogarty, M.J., Rosenberg, A.A., Cooper, A.B., Dickey-Collas, M., Fulton, E.A., Gutiérrez, N.L., Hyde, K.J.W., Kleisner, K.M., Kristiansen, T., Longo, C., Minte-Vera, C.V., Minto, C., Mosqueira, I., Osio, G.C., Ovando, D., Selig, E.R., Thorson, J.T., Ye, Y., 2016. Fishery production potential of large marine ecosystems: A prototype analysis. Environmental Development 17, 211–219. https://doi.org/10.1016/j.envdev.2016.02.001
28. Stuchtey, M., Vincent, A., Merkl, A., Bucher, M., Haugan, P.M., Lubchenco, J., Pangestu, M.E., 2020. Ocean solutions that benefit people, nature and the economy. Washington, DC: World Resources Institute.
29. Gephart, J.A., Agrawal Bejarano, R., Gorospe, K. et al. Globalization of wild capture and farmed aquatic foods. Nat Commun 15, 8026 (2024). https://doi.org/10.1038/s41467-024-51965-8
30. Bartley, D.M., De Graaf, G.J., Valbo-Jørgensen, J., Marmulla, G., 2015. Inland capture fisheries: status and data issues. Fish Manag Ecol 22, 71–77. https://doi.org/10.1111/fme.12104
31. Fluet-Chouinard, E., Funge-Smith, S. and McIntyre, P.B., 2018. Global hidden harvest of freshwater fish revealed by household surveys. Proceedings of the National Academy of Sciences, 115(29), pp.7623-7628.
32. Oyinlola, M.A., Reygondeau, G., Wabnitz, C.C., Troell, M., Cheung, W.W., 2018. Global estimation of areas with suitable environmental conditions for mariculture species. PLoS One 13, e0191086.
33. Blanchard, J.L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J., Holt, J., Dulvy, N.K. and Barange, M., 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1605), pp.2979-2989.
34. Oyinlola, M.A., Reygondeau, G., Wabnitz, C.C., Frölicher, T.L., Lam, V.W., Cheung, W.W., 2022. Projecting global mariculture production and adaptation pathways under climate change. Global change biology 28, 1315–1331.
35. Nash, K.L., MacNeil, M.A., Blanchard, J.L., Cohen, P.J., Farmery, A.K., Graham, N.A.J., Thorne-Lyman, A.L., Watson, R.A., Hicks, C.C., 2022. Trade and foreign fishing mediate global marine

595 nutrient supply. Proc. Natl. Acad. Sci. U.S.A. 119, e2120817119.
596 https://doi.org/10.1073/pnas.2120817119
597 36. Reid, G. K., Gurney-Smith, H. J., Marcogliese, D. J., Knowler, D., Benfey, T., Garber, A. F., ... & De
598 Silva, S. (2019). Climate change and aquaculture: considering biological response and resources.
599 Aquaculture Environment Interactions, 11, 569-602.
600 37. Lam, V. W. Y. et al. Climate change, tropical fisheries and prospects for sustainable development.
601 Nat. Rev. Earth Environ. 1, 440–454 (2020).
602 38. Tigchelaar, M., Cheung, W. W., Mohammed, E. Y., Phillips, M. J., Payne, H. J., Selig, E. R., ... &
603 Troell, M. (2021). Compound climate risks threaten aquatic food system benefits. Nature food, 2(9),
604 673-682.
605 39. Free, C. M., Cabral, R. B., Froehlich, H. E., Battista, W., Ojea, E., O'Reilly, E., ... & Gaines, S. D.
606 (2022). Expanding ocean food production under climate change. Nature, 605(7910), 490-496.
607 40. Cottrell, R.S., Blanchard, J.L., Halpern, B.S., Metian, M., Froehlich, H.E., 2020. Global adoption of
608 novel aquaculture feeds could substantially reduce forage fish demand by 2030. Nature Food 1,
609 301–308.
610 41. Clawson, G., Kuempel, C. D., Frazier, M., Blasco, G., Cottrell, R. S., Froehlich, H. E., ... & Halpern, B.
611 S. (2022). Mapping the spatial distribution of global mariculture production. Aquaculture, 553,
612 738066.
613 42. Liu, Y., Yang, X., Wang, Z., Liu, B., Zhang, J., Liu, X., ... & Zhou, M. (2024). Mapping the fine spatial
614 distribution of global offshore surface seawater mariculture using remote sensing big data.
615 International Journal of Digital Earth, 17(1), 2402418.
616 43. Koehn, J.Z., Allison, E.H., Golden, C.D., Hilborn, R., 2022. The role of seafood in sustainable diets.
617 Environ. Res. Lett. 17, 035003. https://doi.org/10.1088/1748-9326/ac3954
618 44. Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton,
619 P.K., Böttcher, H., Conant, R.T., 2014. Climate change mitigation through livestock system transitions.
620 Proceedings of the National Academy of Sciences 111, 3709–3714.
621 45. James, R., Archer, M., Henderson, J., Garrett, A., 2011. Resource Maps for Fish across Retail and
622 Wholesale Supply Chains.
623 46. Koueta, N., Viala, H., Le Bihan, E., 2014. Applications, uses and by-products from cephalopods, in:
624 Cephalopod Culture. Springer, pp. 131–147.
625 47. Péron, G., François Mittaine, J., Le Gallic, B., 2010. Where do fishmeal and fish oil products come
626 from? An analysis of the conversion ratios in the global fishmeal industry. Marine Policy 34, 815–820.
627 https://doi.org/10.1016/j.marpol.2010.01.027
628 48. Blanchard, J.L. & Novaglio, C., eds. 2024. Climate change risks to marine ecosystems and fisheries
629 – Projections to 2100 from the Fisheries and Marine Ecosystem Model Intercomparison Project. FAO
630 Fisheries and Aquaculture Technical Paper, No. 707. Rome, FAO. https://doi.org/10.4060/cd1379en
631 49. Bussieck, M.R., Meeraus, A., 2004. General algebraic modeling system (GAMS), in: Modeling
632 Languages in Mathematical Optimization. Springer, pp. 137–157.
633 50. Elleby, C., Domínguez, I.P., Nielsen, R. et al. Introducing maximum sustainable yield targets in
634 fisheries could enhance global food security. Commun Earth Environ 6, 33 (2025).
635 https://doi.org/10.1038/s43247-024-01851-4
636 51. Hilborn, R., & Costello, C. (2018). The potential for blue growth in marine fish yield, profit and
637 abundance of fish in the ocean. Marine Policy, 87, 350-355.
638 52. Ihaka, R., & Gentleman, R. (1996). R: a language for data analysis and graphics. Journal of
639 computational and graphical statistics, 5(3), 299-314.
640 53. Shepherd, C. J., & Jackson, A. J. (2013). Global fishmeal and fish-oil supply: inputs, outputs and
641 markets. Journal of fish biology, 83(4), 1046-1066.
642 54. Tacon, A.G., Metian, M., 2008. Global overview on the use of fish meal and fish oil in industrially
643 compounded aquafeeds: Trends and future prospects. Aquaculture 285, 146–158.

55. Tacon, A.G.J., Metian, M., 2015. Feed Matters: Satisfying the Feed Demand of Aquaculture. Reviews in Fisheries Science & Aquaculture 23, 1–10. https://doi.org/10.1080/23308249.2014.987209
56. Wood, S., Wood, M.S., 2015. Package 'mgcv.' R package version 1, 729.
57. Cashion, T., Le Manach, F., Zeller, D., & Pauly, D. (2017a). Most fish destined for fishmeal production are food-grade fish. *Fish and Fisheries*, *18*(5), 837-844.
58. Cashion, T., Tyedmers, P., & Parker, R. W. (2017b). Global reduction fisheries and their products in the context of sustainable limits. *Fish and Fisheries*, *18*(6), 1026-1037.

Supplement 1. Balancing Supply and Demand Data

In 2013, FAO changed their methodology for reporting the Food Balance Sheet (FBS). This results in an overlap in data in the years 2010 – 2013. For this period, we calculate the supply and demand balance for each aggregated commodity group, country, and year. For each of these datapoints we use the dataset that is closer to balanced.

To avoid infeasibilities in running GLOBIOM, demand and supply inputs need to be balanced. Because the datasets provided by FAO are not balanced at either a global scale, or across all regional scales, we performed several data transformations to produce supply and demand values that both reflect values from FAO, but which are also balanced across scales.

The Food Balance Datasheet (FBS) from FAO aggregates demand to five categories; we used a dataset from the International Food Policy Research Institute (IFPRI) to further disaggregate these product categories. For cephalopods, demersal fish, and other molluscs, we maintained the values reported by the FBS, for the rest, we used the values reported in the IFPRI dataset to estimate the proportions of shrimp, salmon, and tuna & pelagic fish that comprise crustaceans, freshwater fish, and marine fish, respectively.

Because we sought to balance supply and demand at the regional scale, we first balanced trade data on the global scale to produce refined estimates of how imports and exports contribute to regional supply and demand, respectively. Unfortunately, not all trade flows from the FAO trade dataset for each fish product for each year are balanced (i.e. aggregated global exports do not equal aggregated global imports). We therefore assumed that underreporting is likely more prevalent than overreporting, and thus, for each year and fish product, the 'true' global trade flow is equal to the greater of the two values, imports or exports. For products and years where these values differ, we proportionally scaled each region's exports and imports accordingly.

The FBS (demand) and Production (supply) datasets from FAO also do not agree on production values for specific fish products in a given year and region. After correcting trade values, as described above, we compared the reported production values from each dataset by calculating the overall balance that each production value yielded. We then adopted the production value that produced the more balanced set of supply and demand values (i.e. where the value of |supply – demand| is minimized).

Following these steps, there emerged several datapoints where either aggregated demand or aggregated supply values had no corresponding demand or supply for a given product in a given year and region. Rather than discard these values, we elected to keep them in the dataset because they were important for maintaining the overall balance of the dataset. Nevertheless, in terms of production these missing values represented only 0.2% of total production and demand in 2000. We therefore imputed production and demand sources for both sets of missing data by calculating the proportion of 'typical' demand or production across 1) a given fishery through time, 2) in a given country across fish products, and 3) a given fish product across countries. We then allocated the unmatched production or demand according to these proportions in the above order of priority.

Finally, because it is most critical that supply and demand balance is maintained at the global level for each species in a given year, and because the resultant aggregated supply more closely matched global fish production from the FAO's high level summary (FAO, 2022), we made the assumption that the supply values were correct and scaled the demand values to match.

Supplement 2. Additional Figures

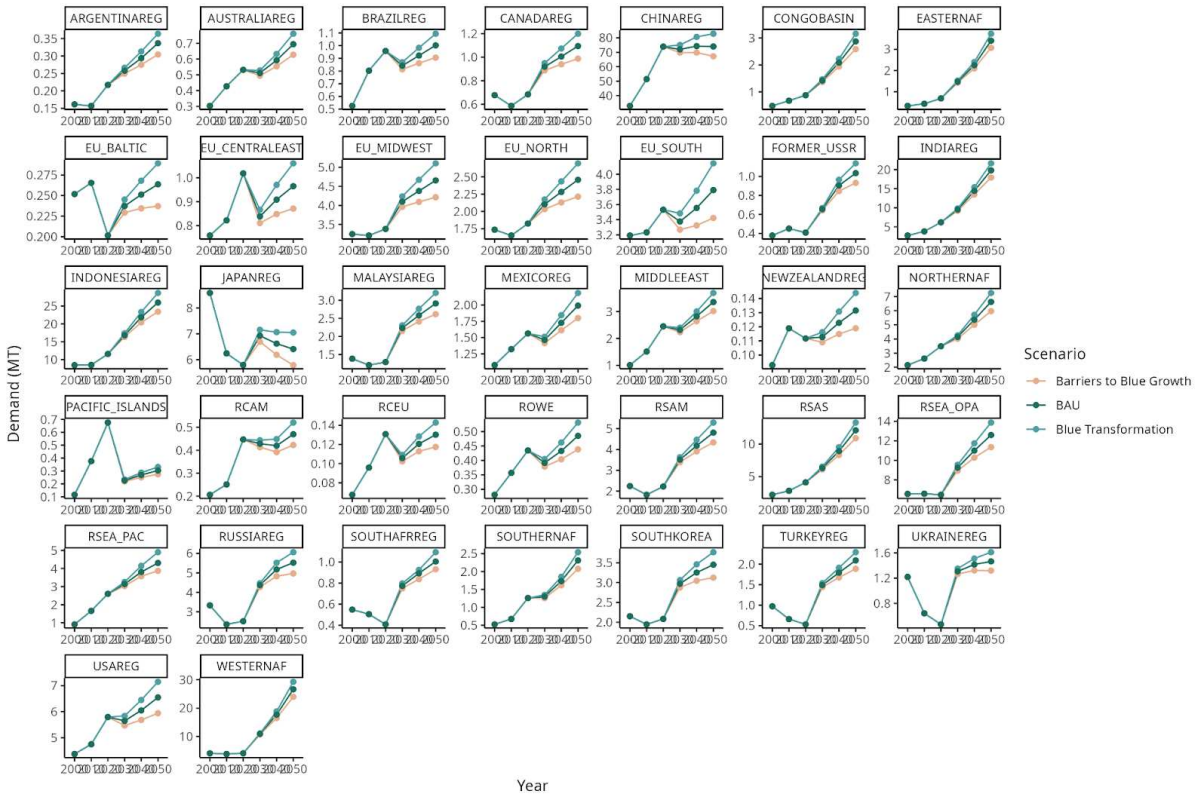


Figure S1. ***Projected seafood demand by region under three scenarios (2000–2050).*** *Regional demand trajectories are shown for Blue Transformation (blue), Business as Usual (green), and Barriers to Blue Growth (orange). Values represent total seafood demand (million tonnes) by region, illustrating how dietary shifts and production constraints influence future consumption patterns across different parts of the world.*

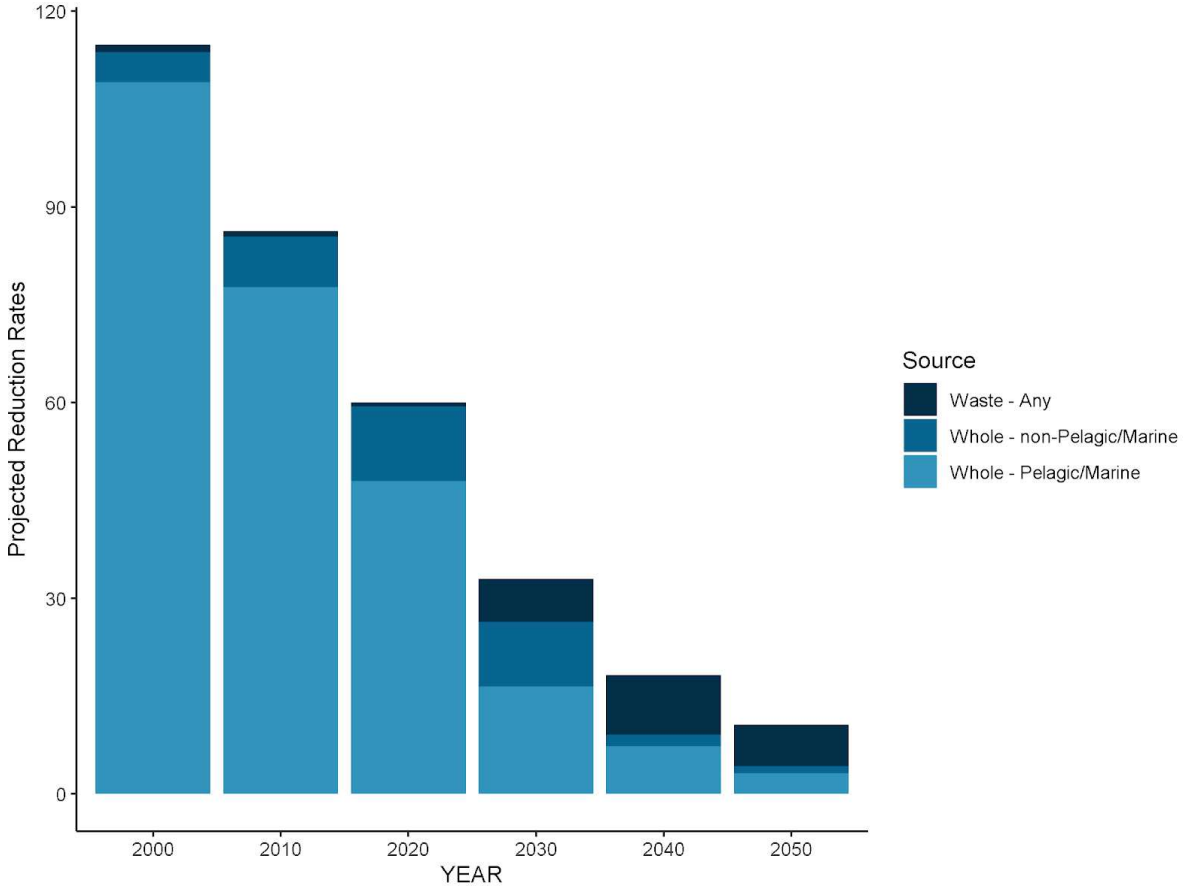


Figure S2. Global trends in sources of biomass reduction for fishmeal and fish oil production (2000–2050). *Bars show the proportion of biomass inputs originating from three sources: whole pelagic/marine fish (light blue), whole non-pelagic/marine fish (medium blue), and processing waste (dark blue). Over time, reliance on whole fish, particularly pelagic species, declines, while the share of processing waste increases, reflecting a projected shift toward more sustainable use of by-products in fishmeal and fish oil production.*

Supplement 3. Fish Aggregations

Table S2. Groups modelled in GLOBIOM

Faostat Production	Fao Food Balance Sheet	Isscaap Group	Globiom
Crabs, Sea-Spiders	Crustaceans	Crustaceans	Crst
King Crabs, Squat-Lobsters	Crustaceans	Crustaceans	Crst
Krill, Planktonic Crustaceans	Crustaceans	Crustaceans	Crst
Lobsters, Spiny-Rock Lobsters	Crustaceans	Crustaceans	Crst
Miscellaneous Marine Crustaceans	Crustaceans	Crustaceans	Crst
Shrimps, Prawns	Crustaceans	Crustaceans	Shri
Shrimps, Prawns	Crustaceans	Crustaceans	Shri
Freshwater Crustaceans	Crustaceans	Crustaceans	Crst
Carps, Barbels And Other Cyprinids	Freshwater Fish	Freshwater Fishes	Carp
Carps, Barbels And Other Cyprinids	Freshwater Fish	Freshwater Fishes	Carp
Carps, Barbels And Other Cyprinids	Freshwater Fish	Freshwater Fishes	Carp
Miscellaneous Diadromous Fishes	Freshwater Fish	Diadromous Fishes	Frsh
Miscellaneous Freshwater Fishes	Freshwater Fish	Freshwater Fishes	Frsh
River Eels	Freshwater Fish	Diadromous Fishes	Frsh
Salmons, Trouts, Smelts	Freshwater Fish	Diadromous Fishes	Salm
Salmons, Trouts, Smelts	Freshwater Fish	Diadromous Fishes	Salm
Shads	Freshwater Fish	Diadromous Fishes	Frsh
Sturgeons, Paddlefishes	Freshwater Fish	Diadromous Fishes	Frsh
Tilapias And Other Cichlids	Freshwater Fish	Freshwater Fishes	Frsh
Flounders, Halibuts, Soles	Demersal Fish	Marine Fishes	Dmrs
Miscellaneous Demersal Fishes	Demersal Fish	Marine Fishes	Dmrs
Cods, Hakes, Haddocks	Demersal Fish	Marine Fishes	Dmrs
Marine Fishes Not Identified	Marine Fish, Other	Marine Fishes	Marn
Sharks, Rays, Chimaeras	Marine Fish, Other	Marine Fishes	Marn
Herrings, Sardines, Anchovies	Pelagic Fish	Marine Fishes	Bait
Miscellaneous Coastal Fishes	Pelagic Fish	Marine Fishes	Marn
Miscellaneous Pelagic Fishes	Pelagic Fish	Marine Fishes	Marn
Tunas, Bonitos, Billfishes	Pelagic Fish	Fishes	Tuna

Squids, Cuttlefishes, Octopuses	Cephalopods	Molluscs	Ceph
Abalones, Winkles, Conchs	Molluscs, Other	Molluscs	Mlsc
Clams, Cockles, Arkshells	Molluscs, Other	Molluscs	Mlsc
Freshwater Molluscs	Molluscs, Other	Molluscs	Mlsc
Miscellaneous Marine Molluscs	Molluscs, Other	Molluscs	Mlsc
Mussels	Molluscs, Other	Molluscs	Mlsc
Oysters	Molluscs, Other	Molluscs	Mlsc
Scallops, Pectens	Molluscs, Other	Molluscs	Mlsc