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An analytical approach to explore prospects and limits of nutrition-sensitive fisheries governance under climate change

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Abstract

Researchers and policymakers increasingly recognize the contribution of aquatic food systems, such as fisheries, to food security and nutrition. Yet governing fisheries for nutrition objectives is complicated by the multiple overlapping processes that shape availability and access to nutrients over time, including fishing sustainability, climate change, trade dynamics, and consumer preferences. Anticipating the effect of governance interventions to sustain or enhance nutritional benefits from fisheries entails accounting for these multiple interacting influences. We develop an analytical approach to link available data on aquatic foods production, nutrition, distribution, and potential climate impacts to evaluate the nutrition implications of fishery management and post-harvest allocation interventions. We demonstrate this approach using national and publicly available datasets for five case study countries: Peru, Chile, Indonesia, Sierra Leone, and Malawi. As examples, we evaluate the potential to enhance domestic supply of key nutrients to nutritionally-vulnerable populations by a) dynamically adjusting fishing effort in response to climate impacts on fish stocks, and b) retaining aquatic foods currently diverted via trade or foreign fishing. The results indicate substantial differences across countries in terms of anticipated climate change effects, with potential for substantially increased nutrition yield in Chile and Peru under adaptive management, vs. more modest yield increases in Indonesia. The impacts of post-harvest allocation policies related to foreign fishing, exports, fishing sector, and subnational trade also vary, with exports weighing heavily on nutrient availability in Sierra Leone. This methodological approach represents a step toward operationalizing calls to manage fisheries as part of national food and nutrient supplies, in light of climate change risks.

Keywords: food systems transformation, aquatic foods, fisheries, climate resilience, climate adaptation, trade, food security, hidden hunger

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1. Introduction

Society must contend with the challenge of sustaining nutritious, equitable, and just food systems in the face of climate change (Vermeulen et al. 2012; Myers et al. 2017; Fanzo et al. 2018). Aquatic food systems (i.e., fisheries and aquaculture), provide nutrition to billions of people and support the livelihoods of millions of households worldwide, although these contributions have not always been fully recognized in food systems policy (Bennett et al. 2021; Golden et al., 2021a). While aquatic foods have potential to contribute to more climate-resilient global food systems (Crona et al. 2023, von Braun et al. 2021), planning specific governance interventions to support this goal is complicated by the multiple interacting processes and factors that shape availability and access to nutrients from aquatic foods.

Recent research highlights key considerations relevant to planning nutrition-sensitive fisheries governance in the context of climate change. First, aquatic foods are rich in multiple nutrients and micronutrients essential to human development, health, and wellbeing (Bennett et al. 2021), with 10 of 15 of the top nutrient-rich animal source food groups in the world are aquatic (Golden et al., 2021a). Nutrient yield varies across species and fisheries (Hicks et al., 2019) and advances in the number and quality of databases on the nutrient content of aquatic foods (Cohen et al., 2022) enable interventions to better account for this variation to understand specific nutritional impacts of more targeted interventions. Early applications of a new concept, Maximum Nutrient Yield, suggest that changes in fishing patterns could increase yield of nutrients needed by target populations without threatening sustainability (Robinson et al. 2022a).

Second, climate hazards including temperature change, acidification, heatwaves, and storm intensity pose serious compounding economic, nutritional, livelihood, and cultural risks for aquatic foods systems (Tigchelaar et al. 2021). Future fisheries declines from overfishing and climate change could result in substantially increased micronutrient deficiencies (Golden et al., 2016; Maire et al., 2021). Climate impacts and risks are not uniform. For example, species ranges are likely to shift poleward and to deeper water with changing temperatures, with the largest impacts in low latitude countries, many of whom already face high rates of malnutrition (Cheung et al. 2023; Whitney et al. 2023). Freshwater systems may be more sensitive to changes in precipitation and water temperature than the oceans (Barange et al. 2018). In some cases, it may be possible to counteract climate impacts through improved fisheries management, for example by reducing overfishing (Cheung et al. 2018; Gaines et al., 2018; Free et al. 2020). In other cases, countries may face inevitable reductions in fisheries due to climate change.

Third, there is increasing awareness among scholars, governments, and donors that governing fisheries for objectives such as livelihoods, gender equity, and nutrition requires interventions not only in harvesting, but also in post-harvest dimensions of food systems (Basurto et al. 2020). Fish is one of the most-traded food commodities in the world, and trade and foreign fishing influence national supply of important nutrients from aquatic foods (Nash et al., 2022). Subsectors within fisheries such as small-scale versus large-scale fleets or foreign fishing often serve distinct end consumers. Within countries, fisheries target different species differentially serving urban or rural, coastal or inland markets (Bennett et al. 2022). Post-harvest approaches to shaping subnational allocation of access to nutrition from fisheries include interventions to reduce food loss and waste, improve market access, reduce transport and transfer costs, and promote consumption of fish products by vulnerable populations such as

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lactating mothers and children under 2 years of age through product development, school feeding, and other nutritional programs (Rice et al. 2023; Ahern et al. 2021).

In this paper, we integrate these three recent strands of research (on nutrient yield, climate impacts, and post-harvest distributional dynamics) into a more holistic analytical approach to evaluating the potential for specific governance interventions to advance nutritional goals of aquatic food systems in the context of climate change. Given the various research efforts, datasets, and alternative management frameworks described above, we aim to provide a practicable approach to bring this information to bear on management decisions to enhance nutrition security. Here, we introduce and provide an initial demonstration of an analytical approach to bring together information on fisheries yield, nutrition, climate-adaptive management, and post-harvest allocation. With context-specific application, this approach has the potential to examine the prospects and limits for aquatic food systems governance to support human nutrition in light of anticipated climate change impacts.

2. Methods

2.1 General approach

Our analytical approach illustrates how different data sources related to fisheries production, allocation, and nutrition can be linked to consider availability and access dimensions of food security in the context of climate change. We use it to evaluate potential nutrition implications of two types of governance decisions: 1) decisions about investment in fisheries management to sustain and enhance nutrient yields and 2) allocative decisions that shape availability of and access to nutrients from aquatic foods at national and subnational (i.e., within specific subpopulations) levels. Recognizing that the type, quality, and quantity of data available for input into such an analytical approach varies across countries and fisheries, we seek to illustrate how different data streams and sources can be integrated to answer similar questions across geographies.

First, the approach considers how different management objectives and interventions affect total nutrient yield, i.e., the total nutrient supply generated from a country's wild capture fisheries (Figure 1, first row). Total nutrient yield is calculated as the product of the edible portion of fisheries production and species-specific nutrient content. Potential management interventions that the approach could consider include those that impact the volume and species composition of fisheries production, with objectives that could include rent maximization, e.g., by achieving maximum economic yield; biodiversity conservation, e.g., by restricting access to slow-reproducing or rare species; or nutrition, e.g., by prioritizing management of and access to highly nutritious species or implementing novel management paradigms like Maximum Nutrient Yield (Robinson et al., 2022a). For exploring future scenarios, climate-adaptive management interventions, such as incorporating climate information into harvest limits or closed areas or implementing joint transboundary management measures, would be key drivers of total nutrient yield. For demonstration purposes in this study, we examine one management intervention related to dynamically maximizing economic yield under climate change (refer to section 2.4). Although this analysis focuses specifically on capture fisheries, a full accounting of a country's aquatic foods total nutrient yield would also include data and analysis of aquaculture (both marine and freshwater; Figure 1).

Next, the approach derives the net nutrient yield, that is, the nutrient yield available to domestic populations (Figure 1, second row). This is calculated by subtracting nutrients diverted to non-domestic uses, which could include exports, foreign fishing, loss and discards, and non-food uses. Here, we focus primarily on exports and foreign fishing due to data availability. Complete accounting of net aquatic

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food nutrients available to domestic populations would also include imports, which we do not discuss in this paper given our focus on domestic production management decisions.

Subnational data on wild caught aquatic foods distribution and consumption among regions and demographics can be used to assess whether aquatic foods nutrients are reaching nutritionally vulnerable populations and potentially reveal barriers to access (Figure 1, third row). The nutrient yield available to specific target groups would be calculated as the sum of the proportion of wild caught aquatic nutrients available to that group (and would additionally include aquaculture nutrients and imported aquatic foods nutrients for a complete accounting). We present one case study focused on subnational allocation to inland and urban populations.

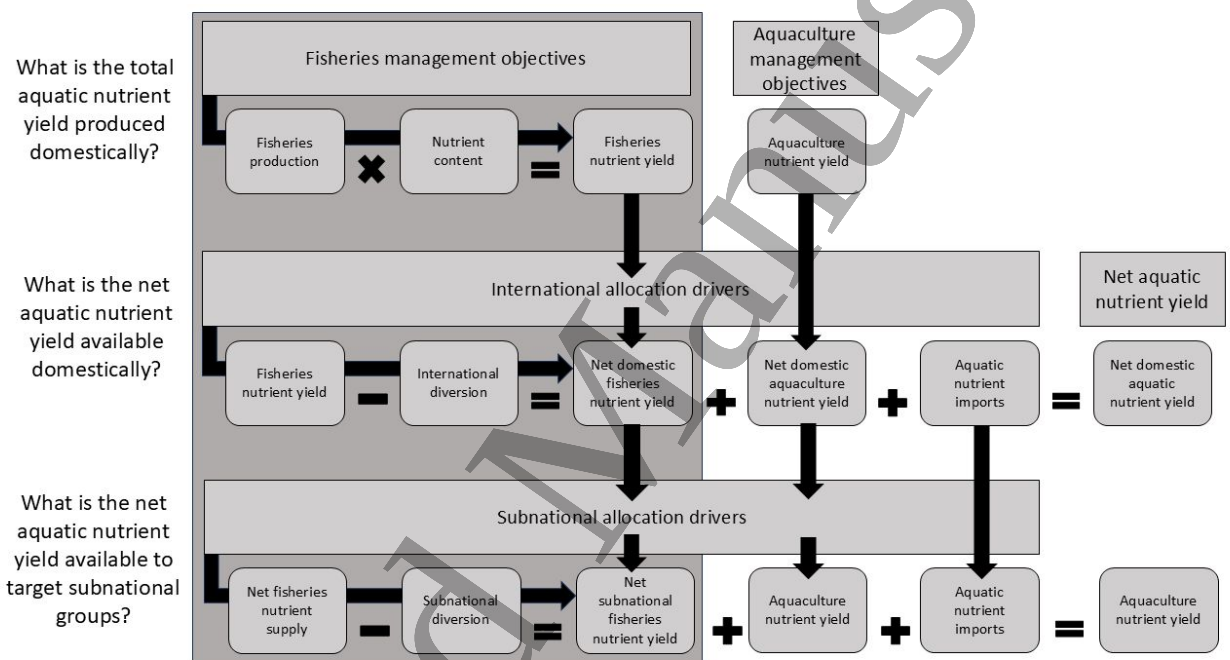

Figure 1: Analytical approach for analyzing current and future aquatic foods nutrient supply to specific populations. Fisheries management objectives and aquaculture management objectives include but are not limited to: rent, employment, livelihoods, nutrition, conservation, cultural benefits, and resilience and adaptive capacity. International allocation drivers (processes diverting nutrients from domestic supply) include but are not limited to: exports, foreign fishing, non-food uses, and loss of waste associated with international supply chains. Subnational allocation drivers include but are not limited to: post-harvest distribution to local and other domestic markets, market segmentation, allocation between small- and large-scale sectors that serve different markets, and loss and waste associated with domestic supply chains. The dark gray box represents the focus of the analysis presented in this paper; drivers outside the box also represent crucial considerations for full aquatic foods nutrition accounting but were not analyzed here.

2.2 *Selection of case study countries and case study contexts*

To illustrate this analytical approach, explore its utility, and identify limitations and challenges in applying it, we selected five country case studies: Peru, Chile, Indonesia, Sierra Leone, and Malawi. In

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case selection, we aimed to a) include at least one case from South America, Asia, and Africa, b) capture variation in latitude, which has relevance for climate impacts on fish abundance and distribution, c) represent both marine and inland (freshwater) fisheries, and d) capture different data types and availability (Table 1). Considering these criteria, we chose major fishing nations for which one or more authors have research experience.

2.2.1 Peru case study background

Peru is home to over 33 million people, 51% of whom experience moderate or severe food insecurity (FAO et al., 2022). Accounting for fortification, 54% of the population is deficient in calcium, 23% is deficient in zinc, 2% is deficient in vitamin A, and 0.01% is deficient in iron (Beal et al., 2017). Despite this low estimation of national iron deficiency, anemia is a public health priority in Peru, with various national programs and policy resolutions to combat childhood and adult anemia rates that rise upward of 40% in the interior Amazon regions (Berky et al., 2020); and a national anemia rate in children aged 6 to 35 months of 43.1%, and in women of childbearing age, aged 15 to 49 years, of 22.7%. Chronic childhood malnutrition is 11.5% in children under 5 years of age (INEI, 2024), influenced by the lack of access to protein-rich foods.

Peru is among the largest fishing nations and is home to the single largest fishery in the world, Peruvian anchoveta (*Engraulis ringens*). Anchoveta comprises the majority of Peru's aggregate catch by volume (68%, 3.9 million tonnes, in 2019; Figure 2a), and most of this catch goes to fishmeal and fish oil production (FAO, 2021; Carlson et al., 2018). Each year, Peru exports over USD 3 billion in total fish and fish products, contributing to 0.55% of national Gross Domestic Product (GDP) (7.93% of agricultural GDP) (FAO, 2021). Peru is the leading exporter of fish for fishmeal and fish oil production globally, exporting over USD 1.5 billion in species destined for fishmeal and nearly USD 375 million toward fish oil annually (Fréon et al., 2014; FAO, 2021).

Following anchoveta stock collapse in the 1970s-80s, fisheries managers implemented individual vessel quota allocations in the anchoveta fishery, which has contributed to stock recovery (Aranda, 2009; Srinivasan et al., 2012). Although most anchoveta are caught by industrial vessels (96.5% of anchoveta landing in 2023; PRODUCE, 2024), the majority of fish caught for direct human consumption in Peru are harvested by the small-scale fleet (De la Puente et al., 2020a) and in case of anchoveta only the small-scale fleet have license to fish it for direct human consumption; small-scale fleets represented 3.5% of anchoveta landing in 2023 (PRODUCE, 2024). Previous attempts to increase domestic demand and consumption of nutrient-rich anchoveta within Peru have been undermined by additional structural issues beyond the industrial vessels' lack of authorization to fish anchoveta for direct human consumption, including higher post-harvest costs associated with products for human consumption and related economic incentives for small-scale fleets to sell anchoveta catch to fishmeal plants, particularly in years when industrial sector quota allocations are low (Majluf et al. 2017). Recent literature suggests a need for improved fisheries management in Peru's small-scale fisheries sector, particularly concerning governance issues such as monitoring and enforcement of illegal fishing (De la Puente et al., 2020a; Gozzer-Wuest et al., 2021). Catch reconstructions have shown a declining trend over the past 20 years, with fluctuations driven largely by anchoveta (Figure 2a) because landings depend on quotas based on scientific recommendations about estimated anchoveta biomass and current and forecasted environmental conditions.

2.2.3 Chile case study background

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The population of Chile has reached almost 20 million people, 17.4% of whom experience moderate or severe food insecurity (INE, 2018; FAO et al., 2022). Accounting for fortification, 58.7% of Chile's population is deficient in calcium, 25.3% deficient in vitamin A, and 9.2% deficient in zinc (Beal et al., 2017).

Like Peru, Chile has a major anchoveta fishery, but the species is less dominant economically and is more often caught by the artisanal sector (99.54% in 2023; SERNAPESCA 2023, Figure S40). Although not examined here, the rapidly-growing aquaculture sector in Chile, predominantly for farmed salmon (*Salmo salar* and *Oncorhynchus* spp.), accounts for nearly half of all domestic seafood production by volume (46% aquaculture; 54% fisheries) (FAO, 2023a; Bachmann-Vargas et al., 2021). Chile exports nearly USD 6 billion worth of fish and fish products each year, accounting for 0.65% of GDP (15.67% of agricultural GDP) (FAO, 2023a; PROCHILE, 2024). Chile has made progress in recent years to address fisheries sustainability challenges through implementation of ecosystem-based fisheries management (Porobic et al., 2018) and co-management mechanisms (Gozzer-Wuest et al., 2023). Catches have been relatively stable over the past decade, with fluctuating anchoveta catches and a marked rise of perch-likes, predominantly jack mackerel/jurel (Figure 4a).

2.2.4 Indonesia case study background

Indonesia is home to around 270 million people, 6% of whom experience moderate or severe food insecurity (FAO et al., 2022). Accounting for fortification, 93.1% of Indonesia's population is deficient in calcium, 85.5% deficient in vitamin A, 6.3% deficient in iron (Beal et al., 2017). In Indonesia, aquatic foods account for over 50% of animal protein intake (FAO, 2022b).

Indonesia is among the largest fishery producers in the world, landing nearly 13 million tonnes of fish and fish products each year, 56% of which comes from fisheries and 44% of which comes from aquaculture (FAO, 2022a). Indonesia exports nearly USD 4.5 billion in fish and fish products annually, contributing to 2.65% of national GDP (20.85% of agricultural GDP) (FAO, 2022a). Indonesian fisheries are dominated by small-scale fishers with highly diverse gear types and target species (Halim et al., 2019; Jaya et al., 2022). To account for this diversity, Indonesia has multiple levels of governance and has moved to decentralize its fisheries management (Jaya et al., 2022). Further, Indonesia has shifted away from single-species management towards an ecosystem-based approach in recent years (Hutubessy & Mosse, 2015; Muawanah et al., 2018). Nonetheless, challenges persist in Indonesian fisheries management including inadequate data and local engagement as well as monitoring and enforcement of regulations (Jaya et al., 2022).

2.2.5 Sierra Leone case study background

Sierra Leone, a coastal nation in West Africa, is home to approximately eight million people, of which 86.7% experience moderate or severe food insecurity (FAO et al., 2022), and about 56.8% of whom live below the national poverty line (UNDP, 2024). Accounting for fortification, 92.4% of the population are deficient in calcium, 60.1% in vitamin A, 50.1% in iron, and 31.3% in zinc (Beal et al., 2017).

Marine fisheries play a critical role in supporting the national economy in Sierra Leone, as well as providing livelihoods to the majority of the country's coastal population, including women, and contributing to food security and nutrition (Thorpe et al., 2009; Thorpe et al., 2014; Baio, 2016). Sierra Leone exports over USD 3 million in fish and fish products annually, accounting for nearly 14% of national GDP (FAO, 2023b). Since the Sierra Leone Civil War (1991-2002) the country's fisheries have faced numerous challenges including increased fishing pressure from illegal gears, foreign industrial

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fleets, and poor governance, despite community-based management efforts (Thorpe et al., 2009; World Bank, 2017; Okeke-Ogbuafor et al., 2020; Okeke-Ogbuafor & Gray, 2021).

2.2.6 Malawi case study background

Malawi's population in 2021 reached 19.89 million, of which 81.3% experience moderate or severe food insecurity (FAO et al., 2022). Accounting for fortification, 95.8% of the population is deficient in calcium, 5.5% deficient in iron, and 0.02% deficient in vitamin A (Beal et al., 2017).

Fish is the most widely consumed animal source protein in Malawi, a landlocked country with large inland fisheries based mainly in two large lakes, Lake Malawi and Lake Chilwa. Fisheries contribute 7% of Malawi's national GDP (Torell et al., 2020), although this may be an underestimate, as landings may be underreported by up to 65% (Fluet-Chouinard et al., 2018). More than 90% of Malawi's fisheries are small-scale, using primarily gillnets and non-motorized vessels targeting small pelagic species, with some larger scale trawl fisheries focused traditionally on tilapia species, but more recently also on pelagics (Cooke et al. 2021).

Usipa (*Engraulicypris sardella*) and other small pelagic species (e.g., Ndunduma, *Diplotaxodon argenteus*; and Utaka, *Mchenga inornata/Copadichromis inornata*) comprise the vast majority of catch by volume (Figure 7a). The predictive models to evaluate nutritional upsides of management under climate change scenarios used on the other case study countries are only applicable to marine fisheries and therefore cannot be applied to Malawi fisheries. However, retrospective observation shows substantial changes in the species composition in landings over the past two decades. Chambo (*Oreochromis* spp., a tilapia) dominated Malawi's landings until the early 1990s when chambo landings declined precipitously. Subsequently, landings of small pelagics rose drastically.

2.3 Calculating total nutrient yield

We used the most recent year of available catch or landings data for each country to characterize current fisheries production, using reconstructed data from the Sea Around Us (SAU) Project database (https://www.seaaroundus.org/) where official national landings were not publicly available (Table 1). In general, SAU reconstructions are more comprehensive than national official landings because they synthesize multiple information sources to interpolate missing data (Zeller & Pauly, 2015). For example, unlike official landings, SAU reconstructions for each exclusive economic zone (EEZ) include catch by foreign vessels, as well as estimates of discards, which is the live weight of fish caught but not retained. Foreign catch and discards by EEZ are both important for characterizing the total potential nutrient yield and the diverse management interventions across the food system in distributing total yield. However, reconstructed data may be less current than official landings and may include assumptions that do not reflect specific country contexts. All catch data represent only marine capture fisheries data, except for Malawi landings, which exclusively represent catch from inland fisheries (Malawi is a landlocked country). Landings data from Chile included substantial harvest of seaweeds and algae, which can be highly nutritious. However, because these taxa are sparsely represented in other data sources, we excluded them from analysis and present their nutrient yield in the supplementary materials.

We sourced nutrient content of finfish from the FishNutrients predictive trait-based model developed by Hicks et al. (2019), which provides estimates of the concentration of calcium, iron, omega-3 fatty acids, selenium, vitamin A, and zinc per 100 grams of an edible serving of each species. Where landings were reported at the genus or family level, we took the mean nutrient content of all species in that genus or family found in that country's EEZ according to FishBase, using the country-level nutrient lookup tool

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that relates FishNutrients data to FishBase species profiles (https://fishbase.ca/Nutrients/NutrientSearch.php). Landings reported at broader taxonomic groups than the family level were excluded from analysis.

We sourced nutrient content of invertebrates and aquatic plants from the Aquatic Foods Composition Database (Golden et al., 2021a), and selected the same nutrients available in the FishNutrients database. Nutrient content was interpolated from genus, family, or order levels where data were missing, as calculated in Golden et al. (2021a). We replaced extreme outlier values (orders of magnitude above other taxa values) with average values from other species within genera, families, or orders depending on data availability. For Humboldt squid (*Dosidicus gigas*), which represents a substantial proportion of Peru and Chile's catch, we used species-specific nutrition information from Bianchi et al. (2022) because nutrients were available only at the family level from the Aquatic Foods Composition Database.

We converted landed weight to edible weight with taxa-level conversion factors (87% for finfish, 36% for crustaceans, 17% for molluscs; Roberts, 1998; Free et al., 2022). For algae, echinoderms, and other species for which we did not have conversion factors, we used landed weight (wet weight). We used a species-specific conversion factor for Humboldt squid (67%; Bianchi et al., 2022) because it represents a substantial proportion of Peru's and Chile's catch. We multiplied total catch or landings by this weight conversion and nutrient concentration to derive total nutrient yield.

To express total nutrient yield in health-relevant terms, we compared nutrient yield to the World Health Organization's (WHO) Recommended Nutrient Intake (RNI) values for children, using mean RNIs for children aged 7 months to 6 years (WHO, 2004). RNIs are daily intake values that would meet the nutrient requirements of 97.5% of the healthy population of a given age and sex. We expressed nutrient yield in child RNI-equivalents, meaning the number of children whose daily nutrient needs could theoretically be met by consuming all the edible yield (annual catch * conversion to edible portion * nutrient content / 365 / RNI). We used this as a standard, public health-relevant metric to compare yields across nutrients and case studies; this does not imply that all aquatic foods yield could be consumed by children, that children would meet all of their daily nutrient needs from consuming fish, or even that these values reflect the actual number of children in a country's population. Rather, we focused on children because aquatic foods nutrients are critical for childhood development and growth (Neumann et al 2002), so children could be considered a common nutritionally vulnerable population across countries (this metric could similarly be used for reproductive age women; see Nash et al. 2022). RNIs have not been set for omega-3 fatty acids, so we used Adequate Intake values for α-Linolenic acids for children aged 7 months to 8 years (Institute of Medicine, 2005; following Nash et al., 2022). For additional context, we provide prevalence of inadequate intake values for each country, using 2011 values that account for fortification (Beal et al., 2017). Prevalence of inadequate intake estimates were not available for selenium or omega-3 fatty acids. Because selenium is required only in trace amounts, nutrient yield in terms of RNI equivalents was often orders of magnitude higher than yield for other nutrients; we thus exclude selenium from most figures to aid interpretability but report values in the text.

Additionally, to present total nutrient yield in terms relevant to each country's specific demographic context, we calculated potential contributions to current and future total population nutrient demand for each country. For this, we paired current and projected demographic data from the United Nations

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Department of Economic and Social Affairs 2022 estimates and projections (UN DESA, 2022) with sex- and age-specific RNIs for each nutrient (WHO, 2004).

2.4 Calculating nutrition impacts of climate change and fisheries management interventions

To illustrate potential scenarios of climate and fisheries management impacts on nutrition, we converted future fish production projections from Gaines et al. (2018) and Free et al. (2020) into nutrient yield. The bioeconomic model developed in these studies calculates potential biomass and catch based on the effects of projected sea surface temperature on species' potential ranges within an EEZ (from Garcia Molinos et al., 2016), as well as different policy scenarios. We examine nutrition implications of two contrasting policy scenarios: 1) No Adaptation, where current (defined as 2012) fishing mortality is maintained at each time step for species that remain wholly in a country's EEZ, and fishing mortality for transboundary stocks starts at 2012 rates and gradually moves toward open access harvest rates and 2) Full Adaptation, where both static and transboundary species are harvested at the rate that achieves Maximum Economic Yield (MEY), dynamically optimized each year for climate impacts. Refer to Gaines et al. (2018) for additional model specifications and dynamic optimization formulas. These policy scenarios are not intended to perfectly replicate how fisheries management does or could operate in a given country, but rather as demonstrations of what these policy goals might look like if achieved. We selected these two scenarios to maximize contrast.

Additionally, the bioeconomic model examines four climate scenarios from the Intergovernmental Panel on Climate Change's suite of Representative Concentration Pathways (RCPs), which characterize alternative future greenhouse gas emissions based on potential socio-economic and technological developments (Moss et al., 2010). We present outputs from one moderate climate scenario (RCP 6.0) for simplicity but provide additional climate scenarios in the supplementary materials.

Because the starting harvest values for each species and country in the bioeconomic model were based on the RAM Legacy Stock Assessment database and Food and Agriculture Organization marine capture databases, which often use different catch history reconstruction techniques and input data than the SAU or national datasets, they do not necessarily align with the production data we used in this analysis. Therefore, rather than comparing projected future catch values from the bioeconomic model directly with our country-specific production data, we first converted the projected catch values into a ratio of future modeled catch to baseline modeled catch. Specifically, we divided the projected catch at mid-century (mean of 2051-2060) in both the No Adaption and Full Adaptation scenarios by the mean catch in 2017-2021 under the No Adaptation scenario. We used this relatively short baseline period to avoid large "burn-in" fluctuations in the initial years of model projections. We then multiplied the country-specific production values by those ratios to adjust the projected catch values. Where landings data were reported at the genus or family level, we took mean projected catch ratios for modeled species for each country. We present catch and nutrition yield projections only for the subset of species for which production and nutrition data were available. We calculated the nutrient "upside" of climate-adaptive management as the difference in mean adjusted projected catch between the two scenarios at mid-century. We express the upside as a proportion of the baseline catch or baseline child RNI equivalents, clipped to the subset of species for which projection data were available.

2.5 Accounting for national-level allocative drivers

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We used SAU estimates to calculate catch by foreign vessels in each country's EEZ (Table 1). Because we could not trace the ultimate destination of foreign-caught fish, we assumed that catch by foreign vessels was consumed by the foreign fishing country and therefore represents a domestic nutrition loss; however, we acknowledge that this may not be the case depending on the species and country, particularly in situations where the foreign access agreement includes a requirement to supply a portion of catch for the domestic market or where there are requirements to land catch domestically, for example, as required in the Palau National Marine Sanctuary Act (PICRC, 2019). Foreign catch data were not available for Malawi.

We used the share of production exported from the Aquatic Resource Trade in Species (ARTIS) database (https://artisdata.weebly.com), which disaggregates bilateral trade data into estimated species flows based on Gephart et al. (2024). We multiplied country-specific production by the proportion exported by volume for each species and country in 2019, the most recent year available in the database. The ARTIS database has been harmonized with SAU species and taxa names, minimizing mismatch. Although export data were available for Malawi, we did not assess them here due to high levels of uncertainty given informal cross-border trade (Mussa et al. 2017) (Table 1).

Other potential national-level allocative drivers include food loss and waste along the supply chain (including discards and spoilage) and the conversion of aquatic foods to uses other than direct human consumption, such as fishmeal or fish oil for agriculture, mariculture, and livestock. Rates of post-harvest loss and uses other than direct human consumption vary at the specific value chain level, including amongst different chains (e.g., dried versus fresh products, local versus export markets), so we did not explicitly examine these drivers here. However, they could be quantified and demonstrated in the same manner as the other allocative measures where data are available, and may be feasible particularly for studies with a narrower focus on a single country or fishery. For Peru and Chile, where conversion to fishmeal/fish oil represents a critical driver because of the predominant anchoveta (*Engraulis ringens*) fishmeal industry (Fréon et al., 2014), we indirectly address this driver by separating our nutrient yield analyses of anchoveta and other species. We present separate figures and values for anchoveta in Peru, and figures for Chile's anchoveta are in the supplemental information. However, this does not account for conversion of other species to fishmeal.

Table 1. Data sources for each case study used to evaluate the nutrition implications of fishery management and post-harvest allocation interventions.

Country	**Production, most recent year**	**Climate-adaptive fishery management**	Exports	**Foreign fishing**	**Fishing sector**	**Subnational distribution**
Peru	Sea Around Us, 2019. (De la Puente et al., 2020b)	Gaines et al. (2018) and Free et al. (2020)	ARTIS trade database	Sea Around Us	Sea Around Us	Not assessed
Chile	Country-specific official landings from SERNAPESCA, 2021	Gaines et al. (2018) and Free et al. (2020)	ARTIS trade databas	Sea Around Us	Official landings	Not assessed

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	(http://www.sernapesca.cl/informacion-utilidad/anuarios-estadisticos-de-pesca-y-acuicultura)		e		from SERNAPESCA	
Indonesia	Sea Around Us, 2019. (Polido et al., 2020)	Gaines et al. (2018) and Free et al. (2020)	ARTIS trade database	Sea Around Us	Sea Around Us	Not assessed
Sierra Leone	Illuminating Hidden Harvest estimates, 2017 (FAO et al., 2018)	Gaines et al. (2018) and Free et al. (2020)	ARTIS trade database	Sea Around Us	Illuminating Hidden Harvest	Not assessed
Malawi	Country-specific official landings from Department of Fisheries Data, 2017	No data	Not assessed	No data	Official landings from Department of Fisheries Data	Sector-level production; Detailed market and value chain analysis (Bennett et al. 2022)

3. Results

Countries vary in terms of the projected impact of climate change in their waters and the current flows of landings out of national waters via foreign fishing and trade, resulting in different levers for retaining fishery nutrients. The selected case studies, detailed below, illustrate a range of predicted future outcomes and different policy and management levers that may influence nutrient availability nationally or for specific subnational populations by mid-century (Table 2).

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Table 2. Summary of total nutrient yield, climate impacts, and potential leverage of national and subnational allocative drivers for each case study used to evaluate the nutrition implications of fishery management and post-harvest allocation interventions. Projected climate impact represents percent (%) change in catch by mid-century (2051-2060) under the No Adaptation scenario. The impact (or upside) of climate-adaptive fishery management is the difference in projected catch in the Full Adaptation scenario and the No Adaptation scenario at mid-century, expressed as a percentage of baseline catch. For allocative drivers, % yield diverted refers to nutrient yield (share of total child RNI equivalents) going to that destination (diverted to exports; diverted to foreign fishing; diverted to inland populations), although we do not assess in this study whether the populations in those destinations are more nutritionally vulnerable than those in the country or region where the fish was caught. For industrial/large-scale fishing, percent (%) yield refers to the percentage of nutrients caught in those fisheries; we specify % yield rather than % yield diverted since these nutrients may be consumed domestically. Categories are defined as: negligible (<2% change in nutrient yield or change in catch); small (2-10% change in nutrient yield or change in catch); modest (11-25% change in nutrient yield or change in catch); moderate (26-40% change in nutrient yield or change in catch); substantial (>40% change in nutrient yield or change in catch). RNI - Recommended Nutrient Intake. RCP - Representative Concentration Pathway. TNY - Total Nutrient Yield.

Country	**Nutrient**	**Total Nutrient Yield (TNY)**		Climate impact and fisheries management upside		National allocative drivers			Subnational allocative drivers	
		Child RNI equivalents	Population demand met (%)	Projected climate impact on catch (Midcentury, RCP 6.0)	Upside of climate-adaptive fishery management, (% of baseline RNIs)	Exports (% nutrient yield diverted)	Foreign fishing (% nutrient yield diverted)	Industrial/Large-scale fishing (% nutrient yield)	Inland (% nutrient yield diverted)	Urban (% nutrient yield diverted)
Peru (anchoveta excluded)				Substantial decrease to 52.4% of baseline	Substantial upside, median 88.7% of TNY	Substantial, median 51.9%	Moderate, median 28.3%	Modest, median 24.0%	Not assessed	Not assessed

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	Calcium	5,030,132	7.6	catch	156.99	43.68	34.78	37.79		
	Iron	13,348,919	17.39		97.3	61.11	28.27	23.96		
	Omega 3s	25,818,214	44.16		67.78	51.89	22.54	14.65		
	Selenium	100,850,392	186.12		74.09	55.55	28.26	22.68		
	Vitamin A	731,364	1.72		201.6	22.73	32.75	49.11		
	Zinc	17,268,854	38		80.03	58.67	24.04	13.79		
Peru (anchoveta only)	Calcium	25,865,920	39.1	Small decrease to 93.6% of baseline catch	Negligible upside, median 0.59% of TNY	Substantial, 77.5%	Small, 2.8%	Substantial, 93.6%		

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	Iron	21,604,962	28.15							
	Omega 3s	136,508,816	233.47						Not assessed	Not assessed
	Selenium	124,488,162	229.74							
	Vitamin A	1,533,288	3.61							
	Zinc	26,372,223	58.04							
Chile (anchoveta excluded)				Substantial decrease to 44.3% of baseline catch	Substantial upside, median 269.3% of TNY	Substantial, median 62.3%	Negligible, median 1.7%	Substantial, median 57.0%		
	Calcium	7,333,104.14	18.05		301.98	62.23	1.70	56.95		
	Iron	11,576,498.3	25.45		295.02	64.44	1.96	59.55	Not	Not

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		2							assessed	assessed
	Omega 3s	19,236,703.84	53.44		232.68	50.57	1.42	39.35		
	Selenium	41,344,460.41	67.39		233.98	58.3	1.61	53.85		
	Vitamin A	65,289,104.96	196.32		254.87	58.56	1.58	56.05		
	Zinc	1,183,050.82	4.62		283.81	62.65	1.65	61.75		
Indonesia				Small decrease to 97.8% of baseline catch	Modest upside, median 11.8% of TNY	Modest, median 16.1%	Small, median 3.0%	Substantial, median 71.72%		
	Calcium	44,923,278	8.26		7.5	15.83	3.04	70.45		
	Iron	30,896,462	4.9		11.95	17.67	2.62	71.72	Not	Not

	Omega 3s	61,518,496	12.69		11.67	16.08	2.84	72.71	assessed	assessed
	Selenium	494,134,576	110.01		17.36	17.26	2.81	71.26		
	Vitamin A	10,532,526	3.01		16.67	13.28	3.54	72.43		
	Zinc	35,574,824	9.49		11.36	15.05	3.13	71.42		
Sierra Leone				Substantial decrease to 31.8% of baseline catch	Negligible upside, median 0.18% of TNY	Moderate, median 25.8%	Modest, median 16.5%	Moderate, median 33.3%		
	Calcium	2,797,762	19.22		0.24	30.57	10.94	33.76		
	Iron	2,049,560	11.98		0.11	25.78	16.9	31.83	Not assessed	Not assessed
	Omega 3s	6,694,476	52.41		-1.91	14.85	13.42	25		

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	Selenium	37,382,831	314.04		1.22	28.66	16.45	34.93		
	Vitamin A	428,075	4.42		6.72	39.32	20.07	48.92		
	Zinc	2,711,459	25.77		-1.74	20.91	15.65	27.84		
Malawi				No data	No data	Not assessed	No data	Negligible, median 1.29%	Substantial, median 93.46%	Substantial, median 67.67%
	Calcium	4,082,242	11.51					0.74	94.22	66.93
	Iron	2,825,807	6.69					0.66	93.99	67.29
	Omega 3s	1,909,464	6.2					1.51	93.53	68.03
	Selenium	12,626,473	43.85					1.29	93.38	68.26

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	Vitamin A	668,233	2.82					2.00	93.98	67.31
	Zinc	2,037,411	7.91					1.23	93.29	68.97

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3.1 Peru

3.1.1 *Results in brief – Key drivers: export and foreign fishing allocations, climate-adaptive management*

While climate change could cause a substantial decline in nutrient yield by mid-century for Peru, there is an opportunity for climate-adaptive management to improve nutrient yields relative to current baseline. Currently, a substantial proportion of Peru's nutrient yield is diverted away from domestic consumption through exports and presumed diversion of anchoveta to fishmeal/fish oil production. Foreign fishing of species other than anchoveta also currently diverts a moderate proportion of nutrient yield.

3.1.2 *Current total nutritional yield from capture fisheries*

Peru's 2019 catch, excluding anchoveta, represents a Total Nutrient Yield (TNY) equivalent to over 13 million child RNIs for iron, or over 100 million child RNIs for selenium (Figure 2b, Table 2). This catch represents ample sources of selenium, omega-3 fatty acids, zinc, and iron for Peru's population (Table 2). Although most anchoveta is not consumed by humans, Peru's anchoveta TNY represents over 20 million child RNI equivalents for all assessed nutrients except vitamin A, and could exceed Peru's population-level demand for omega-3 fatty acids and selenium (Table 2). Of the five most commonly caught species by volume in the SAU catch data, anchoveta represents a major source of omega-3 fatty acids, with a 100g edible serving providing over 100% of a child's daily RNI (Figure 2c). Humboldt squid and jurel (jack mackerel; *Trachurus murphyi*) provide substantial iron, omega-3 fatty acids, and zinc; jurel is additionally a good source of calcium. Bonito (*Sarda chiliensis*) is a source of iron and omega-3 fatty acids (Figure 2c).

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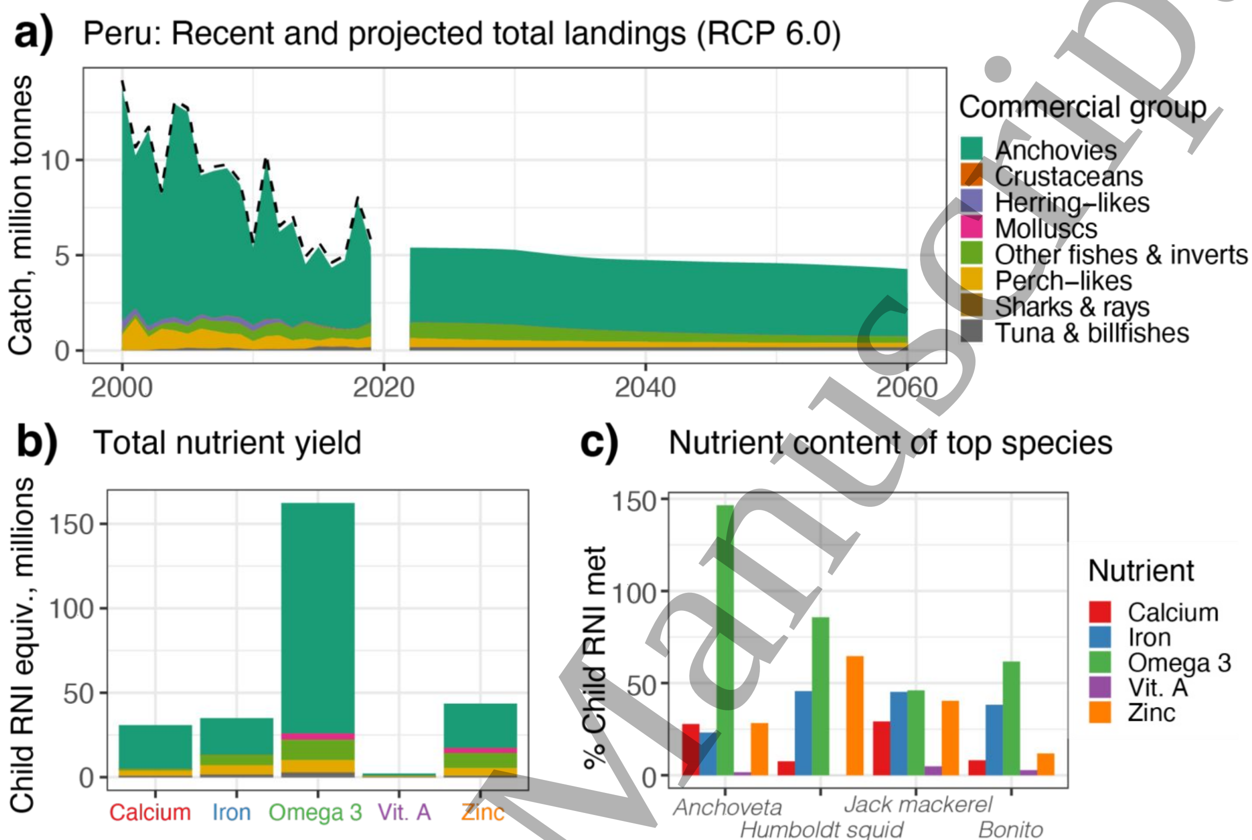

Figure 2: Nutrient yield for Peru. a) Past and projected catch in Peru under a No Adaptation management scenario and Representative Concentration Pathway (RCP) 6.0. Past landings from Sea Around Us (SAU; https://www.seaaroundus.org). Catch projections from Free et al. (2020), adjusted to 2019 SAU catch values. Dotted line represents all catch data from SAU, while colored areas are the subset of species for which projection data are available. Colors are broad commercial groups defined by SAU. Refer to Figure S1 for full SAU catch data. b) Total nutrient yield (TNY) from reconstructed catch in 2019, expressed in terms of Recommended Nutrient Intake (RNI) equivalents for children aged 7 months-6 years. Colors represent commercial groups from SAU (refer to panel a). Refer to Figure S2 for TNY with anchoveta excluded. c) Nutrient content of most caught species by volume, in terms of % daily child RNIs met by consuming a 100g edible portion. Species are ordered by overall most nutrient-dense to least, calculated as the sum of the bars.

3.1.3 *Nutritional upsides and downsides (net nutritional yields) of management and allocation drivers*

Under a No Adaptation management scenario, the total catch from Peru's fisheries, excluding anchoveta, is projected to decrease to 52.4% of the 2017-2021 baseline by mid-century (2051-2060) (Figure 2a, Figure S12). In contrast, under the Full Adaptation scenario, catch could increase to 137.7% of baseline by mid-century (Figure S12). The Full Adaptation scenario would particularly increase yields of calcium (157% of baseline, or 7.7 million child RNI equivalents) and vitamin A (201.6% of baseline TNY, 1.3 million child RNI equivalents) (Figure 3a, Table 2). For anchoveta, the two management scenarios have similar patterns, projecting a small decline in catch by mid-century (to ~94% of baseline

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catch) (Figure S14). Implementing the Full Adaptation scenario instead of the No Adaptation scenario could yield an additional 800,000 omega-3 fatty acid child RNI equivalents at mid-century from anchoveta (Figure 3c, Table 2).

Excluding anchoveta, 47.5% of domestic catch volume is exported. This represents a substantial loss of domestic nutrient yield, from 22.7% of vitamin A yield to 61.1% of iron yield (Figure 3b, Table 2). Iron, zinc, and selenium are slightly overrepresented in export flows, whereas calcium and vitamin A are disproportionately retained in-country (Table 2). The majority, 77.5% by volume, of anchoveta catch is exported. A hypothetical, albeit unrealistic, scenario in which all anchoveta are retained domestically and allocated to direct human consumption, would provide additional nutrient yields equivalent to 102.8 million omega-3 fatty acids child RNIs (Figure 3d, Table 2).

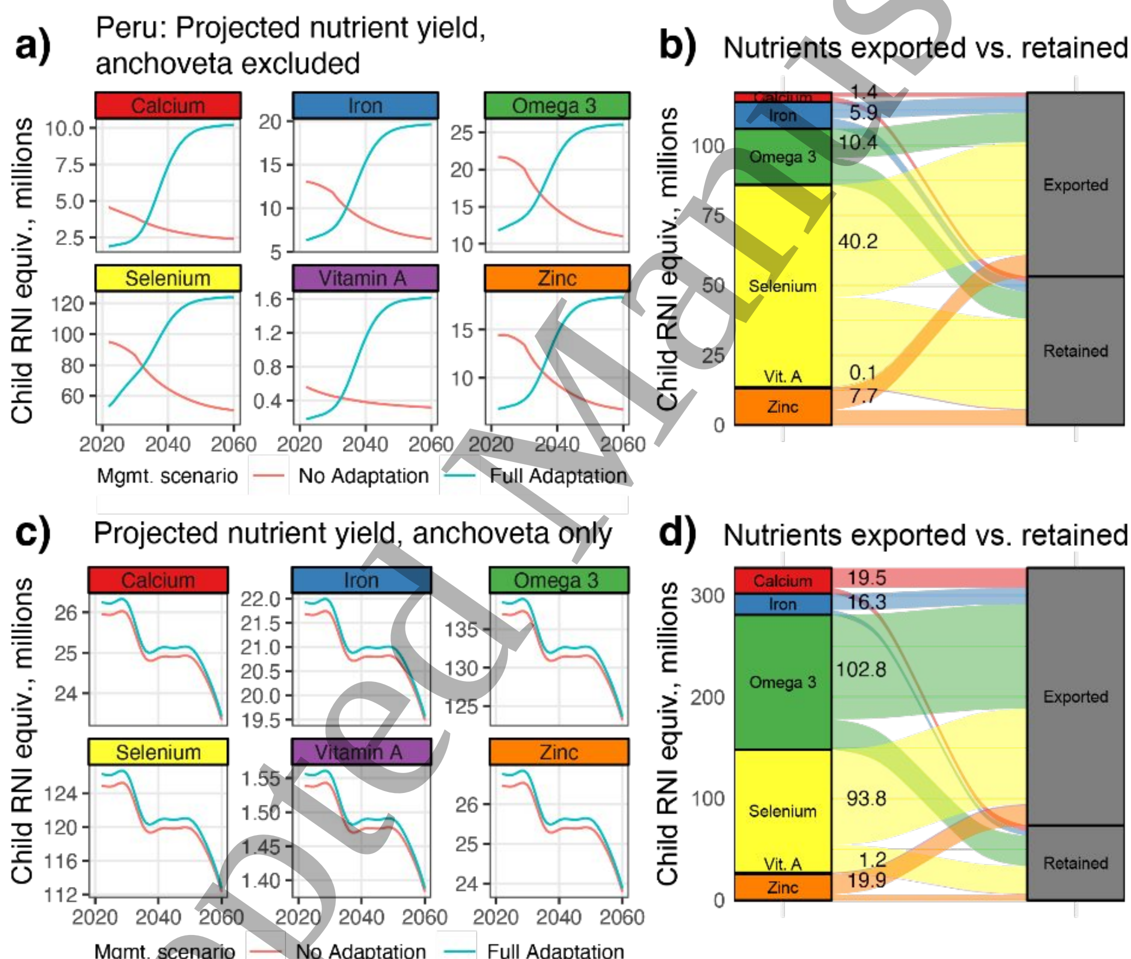

Figure 3: Projected nutrient yield in Peru under a No Adaptation (red) and Full Adaptation (blue) management scenario for Representative Concentration Pathway (RCP) 6.0 from 2022-2100 for catch excluding anchoveta (a) and anchoveta only (c). Catch projections from Free et al. (2020), adjusted to 2019 Sea Around Us (SAU) catch values (https://www.seaaroundus.org/)*. Nutrient yield allocated to exports vs. what is retained domestically in Peru for catch excluding anchoveta (b), and anchoveta only (d). Data from ARTIS (https://artisdata.weebly.com). Numbers on nutrient flows indicate the number of child Recommended Nutrient Intake (RNI) equivalents in millions.*

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Non-anchoveta catch lost to foreign fishing in Peru's waters represents 23.0% of catch volume and a moderate loss of nutrient yield, ranging from 22.5% of omega-3 yield lost to foreign fishing to a 34.8% loss in calcium yield (Figure S37, Table 2). Foreign catch of anchoveta is minimal (<3% by volume) but could still account for 3.8 million child RNI equivalents of omega-3 fatty acids (Figure S38, Table 2).

Artisanal fisheries contribute 81.3% of non-anchoveta catch volume and disproportionately contribute to omega-3 fatty acids and zinc yields (~86% of nutrient yield, representing 17.1 million and 11.3 million child RNI equivalents, respectively), whereas industrial fisheries disproportionately contribute to vitamin A (52% of nutrient yield, representing 240,000 child RNI equivalents) and calcium (37% of nutrient yield, representing 1.2 million child RNI equivalents) (Figure S37, Table 2).

3.2 Chile

3.2.1 *Results in brief – Key drivers: climate-adaptive management, export allocations*

Chile has a similar ecosystem and suite of fished species to Peru, but as a higher-latitude country is projected to see smaller losses in nutrient yield due to climate change and could experience greater increases in nutrient yield by adopting climate-adaptive management reforms. As with Peru, exports represent a substantial diversion of nutrient yield away from domestic consumption, but unlike Peru, foreign fishing represents a negligible nutrient allocation driver.

3.2.2 *Current total nutritional yields from wild fisheries*

Excluding anchoveta and algaes, TNY from Chile's landings could exceed population-level demand for omega-3 fatty acids and selenium, and represents significant supplies of zinc, calcium, and iron (Figure 4b, Table 2). When seaweeds are included in the total nutrient RNI equivalents, these figures more than double for most nutrients except vitamin A, with over a nine-fold increase in zinc provisioning (Figure S5). Although some seaweeds are consumed locally, and a number of government programs have sought to increase domestic consumption of seaweeds (Rogel-Castillo et al. 2023), we do not have definitive figures regarding rates of domestic human consumption. The highest-volume species are similar to those in Peru; Araucanian herring (*Strangomera bentincki*) additionally represents a major source of omega-3 fatty acids (Figure 4c).

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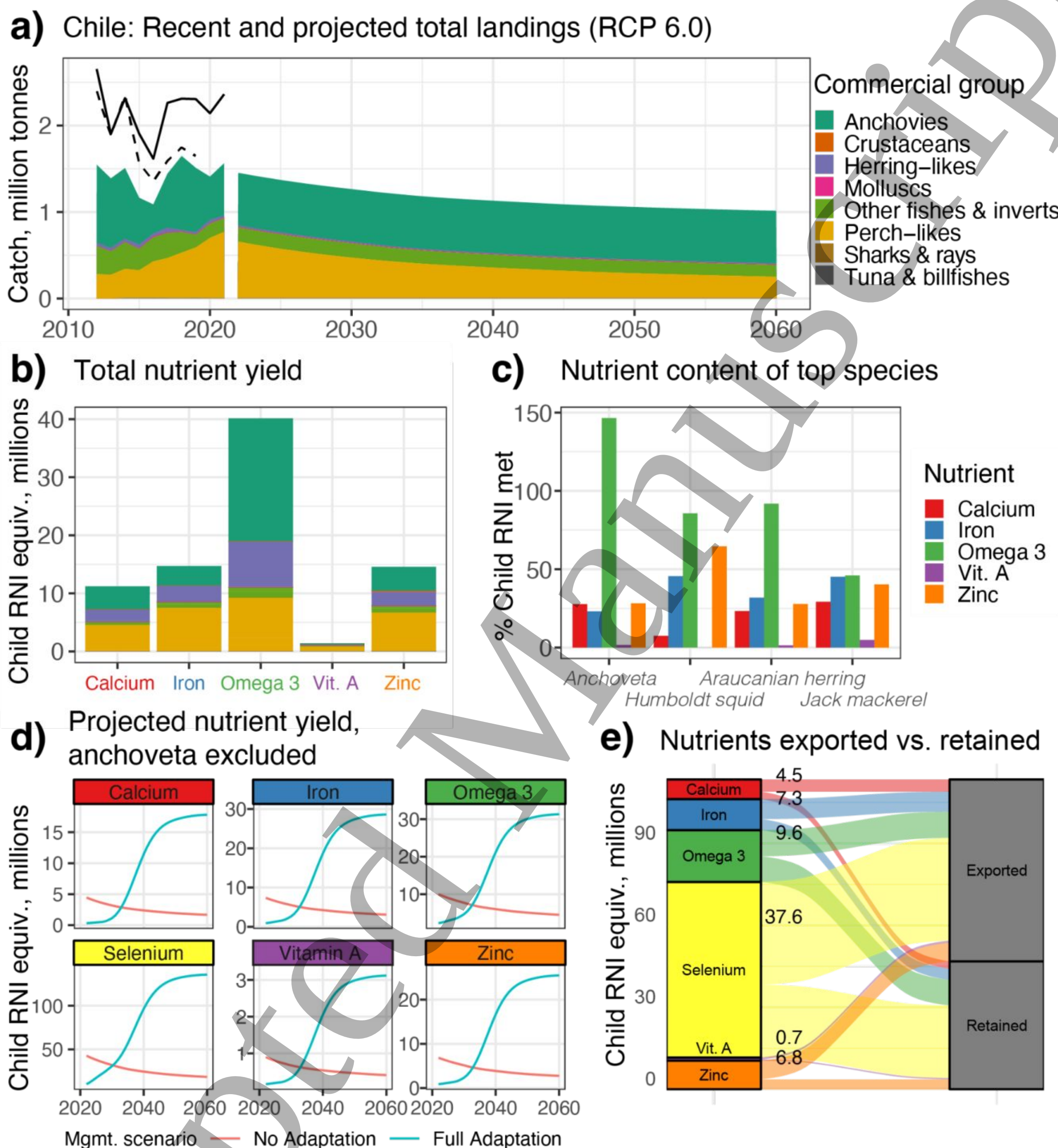

Figure 4: Nutrient yield and allocations for Chile, excluding seaweeds. a) Past and projected catch in Chile under a No Adaptation management scenario and Representative Concentration Pathway (RCP) 6.0. Official national landings from SERNAPESCA (http://www.sernapesca.cl/informacion-utilidad/anuarios-estadisticos-de-pesca-y-acuicultura) and catch projections from Free et al. (2020), adjusted to 2021 catch values. Solid line represents all catch data from SERNAPESCA, while colored areas are the subset of species for which projection data are available. Dotted line indicates all catch data for Chile from the Sea Around Us (SAU) project (https://www.seaaroundus.org/). Colors are broad commercial groups defined by SAU. Refer to Figure S3 for full official landings data and Figure S4 for full SAU catch data. b) Total nutrient yield (TNY) from official catch in 2021, expressed in terms of Recommended Nutrient Intake

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(RNI) equivalents for children aged 7 months-6 years. Colors represent commercial groups from SAU (refer to panel a). Refer to Figure S5 for TNY including algaes and Figure S6 for TNY excluding anchoveta c) Nutrient content of most caught species by volume, in terms of % daily child RNIs met by consuming a 100g edible portion. Species are ordered by overall most nutrient-dense to least, calculated as the sum of the bars. d) Projected nutrient yield, excluding anchoveta, under a No Adaptation (red) and Full Adaptation (blue) management scenario for RCP 6.0 from 2022-2100. e) Nutrient yield, excluding anchoveta, allocated to exports vs. what is retained domestically. Data from ARTIS (https://artisdata.weebly.com). Numbers on nutrient flows indicate the number of child RNI equivalents in millions.

3.2.3 Nutritional upsides and downsides (net nutritional yields) of management and allocation drivers

Under a No Adaptation scenario, non-anchoveta catch is projected to decrease to 44.3% of baseline by mid-century, while under Full Adaptation scenario, catch could increase to 269.3% of baseline, representing substantial nutrient upsides with particular increases in calcium, iron, and zinc. (Figure 4d, Figure S18, Table 2). These large increases are driven by a combination of expected stock range increases in Chile's waters consistent with poleward shifts in stock distributions, and climate-sensitive harvest controls, which forestall modeled collapses in key commercial fish stocks such as jurel and chub mackerel (*Scomber japonicus*) (Free et al., 2020).

The majority (56.9%) of Chile's domestic catch volume is exported, representing a substantial loss in domestic nutrient yields (Table 2). Zinc and iron are overrepresented in export flows relative to volume, while omega-3 fatty acids are underrepresented (Figure 4e, Table 2). Foreign fishing in Chile's waters is negligible according to the SAU database, accounting for just 1.1% of catch volume; nutrient yield losses from foreign fishing are roughly proportional to catch volume, although omega-3 fatty acids are slightly underrepresented in foreign catch (0.68% of nutrient yield lost to foreign fishing) (Figure S39, Table 2). Large-scale fisheries produced the slight majority (50.4%) of Chile's non-anchoveta fishery volume in 2021, with a disproportionate contribution to vitamin A and iron yields because that catch is predominantly jurel/jack mackerel (Table 2). Artisanal fisheries, which catch higher volumes of Araucanian herring and Humboldt squid, disproportionately contributed to omega-3 fatty acids yield (Table 2). Additionally, Chile's artisanal fisheries caught 83% of anchoveta in 2021, representing another major contribution to omega-3 fatty acids yield that is likely diverted to fishmeal and fish oil (Figure S40).

3.3 Indonesia

3.3.1 *Results in brief – Key drivers: climate-adaptive management, export allocations*

Among the countries studied here, Indonesia's catch is uniquely rich in vitamin A, a nutrient for which much of the population faces deficiencies. Because relatively little of Indonesia's nutrient yield is diverted to exports or foreign fishing, further analysis of subnational allocative drivers would be an important step toward distributing that vitamin A yield to nutrient-deficient populations. Small projected climate-related declines in nutrient provisioning could be reversed by mid-century with climate-adaptive management.

3.3.2 *Current total nutritional yields from wild fisheries*

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Indonesia's fisheries TNY represents a larger source of vitamin A relative to the other cases analyzed here, and a large source of selenium, omega-3 fatty acids, and calcium (Figure 5b, Table 2). The high vitamin A yield is driven by relatively high catch of yellowstripe scad (*Selaroides leptolepis*), snappers (*Lutjanus* spp.), chocolate hind (*Cephalopholis boenak*), and fusiliers (*Caesionidae* spp.), all of which have predicted vitamin A values of > 100mcg/100g edible portion.[1] Among commonly-caught species, short mackerel (*Rastrelliger brachysoma*) provides high levels of calcium, iron, and zinc; *Sardinella* spp. are also good sources of calcium, and yellowstripe scad contains high levels of vitamin A (Figure 5c). Narrow-barred Spanish mackerel (*Scomberomorus commerson*) also provides relatively high levels of omega 3 fatty acids (Figure 5c).

[1] The only species with available nutrient data found in Indonesia's waters is the mottled fusilier (*Dipterygonotus balteatus).*

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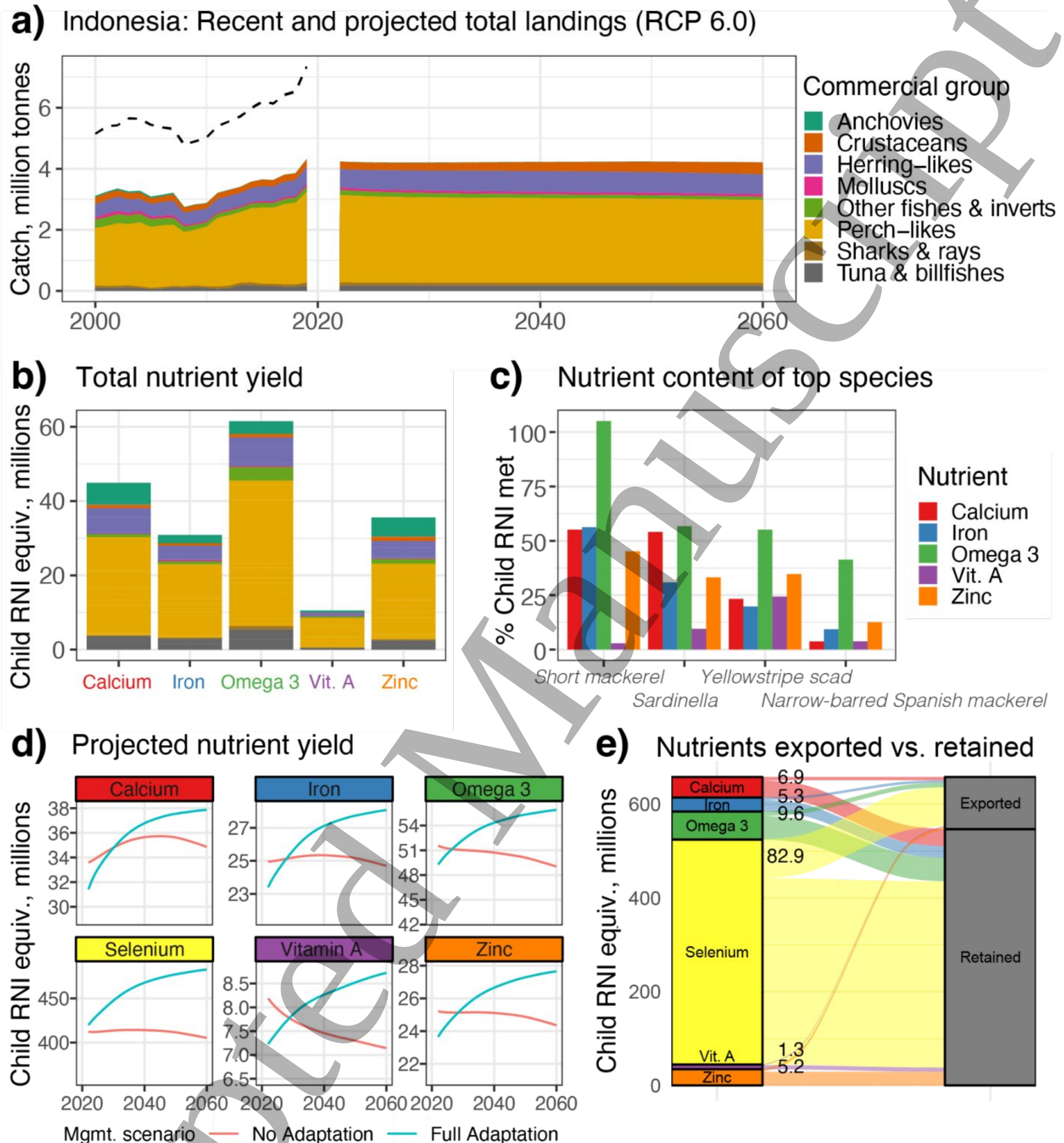

Figure 5: Nutrient yield and allocations for Indonesia. a) Past and projected catch in Indonesia under a No Adaptation management scenario and Representative Concentration Pathway (RCP) 6.0. Past landings from Sea Around Us (SAU; https://www.seaaroundus.org). Catch projections from Free et al. (2020), adjusted to 2019 SAU catch values. Dotted line represents all catch data from SAU, while colored areas are the subset of species for which projection data are available. Colors are broad commercial groups defined by SAU. Refer to Figure S8 for full SAU catch data. b) Total nutrient yield from reconstructed catch in 2019, expressed in terms of Recommended Nutrient Intake (RNI) equivalents for children aged 7 months-6 years. Colors represent commercial groups from SAU (refer to panel a). c) Nutrient content of most caught species by volume, in terms of % daily child RNIs met by consuming a

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100g edible portion. Species are ordered by overall most nutrient-dense to least, calculated as the sum of the bars. d) Projected nutrient yield under a No Adaptation (red) and Full Adaptation (blue) management scenario for RCP 6.0 from 2022-2100. Catch projections from Free et al. (2020), adjusted to 2019 SAU catch values. e) Nutrient yield allocated to exports vs. what is retained domestically. Data from ARTIS (https://artisdata.weebly.com). Numbers on nutrient flows indicate the number of child RNI equivalents in millions.

3.3.3 Nutritional upsides and downsides (net nutritional yields) of management and allocation drivers

Indonesia's fisheries production is projected to decline slightly under climate change and a No Adaptation scenario (Figure 5a, Table 2), but the Full Adaptation scenario could yield nutrient upsides by mid-century, representing 7.5-16.7% increases over baseline TNY for each nutrient (Figure 5d, Table 2).

Exports are a relatively small driver for nutrition yield, redirecting 13.2% of domestic catch volume; however, nutrition yields of iron and selenium are slightly overrepresented in export flows (Figure 5e, Table 2). Foreign fishing is negligible in Indonesia's waters, representing 2.9% of catch volume and similar percent losses in nutrient yield (Figure S41, Table 2). Indonesia's artisanal fisheries contribute approximately one-third of catch volume, and slightly under-contribute to nutrition provisioning relative to industrial fisheries (27.2-29.6% of RNI equivalents) (Figure S41).

3.4 Sierra Leone

3.4.1 Results in brief – Key drivers: export allocations, subnational allocation

In the Sierra Leone case, examining catch as nutrient yield reveals that exports of aquatic foods, while relatively modest in terms of volume, are disproportionately nutritious. Reexamining any national- and subnational allocative drivers that divert nutrition away from vulnerable populations will be critical in Sierra Leone because model projections indicate that nutrient yields will decline substantially due to climate change under all management scenarios. In particular, exports of small pelagic fish disproportionately divert nutrition, representing nearly 40% of Vitamin A yield despite a relatively modest volume. The observably increasing export of smoked fish to Europe and North American in response to demand from African diasporans is of domestic food fish insecurity concern (Baio, 2016). Moreover, the strict monitoring of the 5 nautical miles Inshore Exclusion Zone (IEZ) has resulted in the outsourcing of the harvesting of desired species (especially the bobo croaker, *Pseudotolithus* spp.) to small-scale fishers by traditional industrial fishing operators. The understanding is that the catch should be sold to export oriented fish processing units—an arrangement with potential food fish and nutrition insecurity as well as unsustainability outcomes (Baio, 2016). Sierra Leone represents a case where fisheries management interventions could incur nutrition trade-offs, where restricting fishing to achieve MEY would reduce near-term nutrient availability.

3.4.2 Current total nutritional yields from wild fisheries

Small pelagic "herring-like" fish including Bonga shad (*Ethmalosa fimbriata*) and *Sardinella* spp. contribute to high nutrient yields of omega-3 fatty acids, calcium, zinc, and iron in Sierra Leone's fisheries that could meet a significant portion of population nutrient demand (Figure 6b, Table 2). These species represent major sources of omega-3 fatty acids (Figure 6c). Bonga shad is additionally relatively high in zinc, while *Sardinella* spp. are relatively high in calcium and vitamin A. Lesser African threadfin (*Gaeleoides decadactylus*) and bobo croaker (*Pseudotolithus elongatus*) are also good sources of omega-3 fatty acids (Figure 6c).

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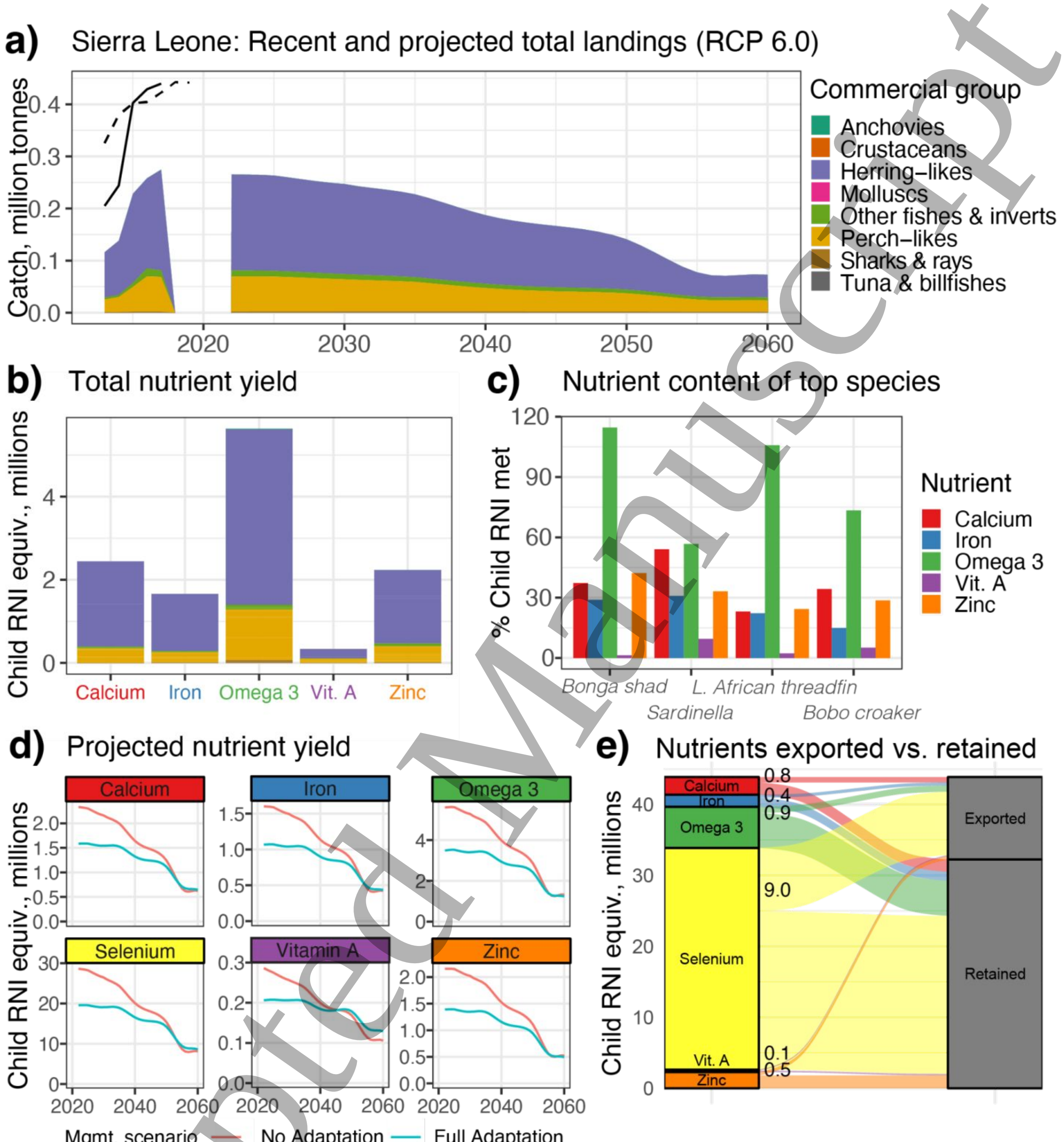

Figure 6: Nutrient yield and allocations for Sierra Leone. a) Past and projected catch in Sierra Leone under a No Adaptation management scenario and Representative Concentration Pathway (RCP 6.0). Reconstructed landings from the Illuminating Hidden Harvest (IHH) project (https://www.fao.org/voluntary-guidelines-small-scale-fisheries/ihh/en) and catch projections from Free et al. (2020), adjusted to 2017 catch values. Solid line represents all catch data from IHH, while colored areas are the subset of species for which projection data are available. Dotted line indicates all catch data for Sierra Leone from the Sea Around Us (SAU) project (https://www.seaaroundus.org/). Colors are broad commercial groups defined by SAU. Refer to Figure S9 for full landings estimates and Figure S10 for full SAU catch data. b) Total nutrient yield from catch in 2017, expressed in terms of

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Recommended Nutrient Intake (RNI) equivalents for children aged 7 months-6 years. Colors represent commercial groups from SAU (refer to panel a). c) Nutrient content of most caught species by volume, in terms of % daily child RNIs met by consuming a 100g edible portion. Species are ordered by overall most nutrient-dense to least, calculated as the sum of the bars. d) Projected nutrient yield under a No Adaptation (red) and Full Adaptation (blue) management scenario for RCP 6.0 from 2022-2100. Catch projections from Free et al. (2020), adjusted to 2017 catch values. e) Nutrient yield allocated to exports vs. what is retained domestically. Data from ARTIS (https://artisdata.weebly.com). Numbers on nutrient flows indicate the number of child RNI equivalents in millions.

3.4.3 Nutritional upsides and downsides (net nutritional yields) of management and allocation drivers

Regardless of the management scenario, nutrient yields from Sierra Leone's fisheries are projected to decrease substantially by mid-century (Figure 6a, 6d, Table 2). In the near term, the Full Adaptation scenario would result in lower nutrient yields than the No Adaptation scenario, due to constraining harvest of overexploited and/or transboundary stocks to achieve MEY (Figure 6d).

Therefore, allocation drivers may be higher priority nutrition interventions. Export flows from Sierra Leone, while only 13.9% of domestic catch volume, represent disproportionate losses of yield for every nutrient analyzed. Vitamin A and calcium, nutrients for which the majority of Sierra Leone's population faces deficiencies, are substantially overrepresented in export flows (Figure 6e, Table 2). This disproportionate loss is primarily driven by export of Sardinella spp. (71% of catch by volume is exported; this represents 93% of export volume analyzed here), which is relatively high in calcium and vitamin A, among other nutrients (Figure 6c).

Foreign catch, at 24.7% of overall catch volume in Sierra Leone's waters, represents a larger driver than exports by volume. But, conversely to exports, foreign catch portfolios are lower in the focal nutrients in this study than domestic catch, particularly lower in calcium and omega-3 fatty acids (Figure S42, Table 2). Small-scale fisheries dominate catch volume (75.4%) and therefore provide the majority of nutrient yield. However, large-scale fisheries disproportionately contribute to nutrient yield for vitamin A and, to a lesser extent, calcium, and iron, due to high catch proportion of Sardinella spp. (Figure S42, Table 2). Even though small-scale fisheries catch relatively more vitamin A-rich snappers (Lutjanus spp., 81 mcg/100g edible serving) than large scale fisheries, small-scale catch is dominated by Bonga shad, which is low in vitamin A (~5 mcg/100g edible serving) compared to Sardinella (~40mcg/100g edible serving (Figure 6c). As Baio (2010) observed, the demersal species occurring in relatively low volume and therefore attracting comparatively high prices, such as snappers and groupers, are regarded as the so-called "Good Fish" in fisheries circles. Conversely, the nutritious clupeids such as Bonga shad and *Sardinella* spp. sustain the majority of the population as the key source of animal protein. However, because these species occur in large quantities due to their shoaling characteristics and consequently are relatively affordable, they are not considered as "Good Fish." This "paradox of value" potentially undermines both the required robust management planning and appropriate pricing for these species.

3.5 Malawi

3.5.1 Results in brief – Key drivers: subnational allocation

This case demonstrates how changes in species composition of landings can affect nutrient provisioning, both because of differences in the nutrient profiles between species and because of post-harvest distributional dynamics. It also illustrates how different species make these nutrients available to distinct populations, due to post-harvest distribution and market dynamics.

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Since Malawi is a landlocked country, it only has inland fisheries and consequently data, estimates, and models of marine fisheries are not available for Malawi. However, this case draws on publicly available subnational postharvest distribution data based on a large value chain survey (Bennett et al. 2021) to explore availability of nutrients from different fisheries to different subpopulations. In Malawi, nutrient provision has evolved with changing fishery species marked by a decline of tilapia species and increase in small pelagic species. Nutrients from these fisheries are differentially available to urban and rural populations, and this varies by species. For example, in Malawi, the small pelagic species usipa (*Engraulicypris sardella*) is much more available in rural markets than chambo (*Oreochromis spp*.), a popular tilapia, which is most available in urban markets (Bennett et al. 2022).

3.5.2 Current total nutritional yields from wild fisheries

Total nutrient yield from Malawi's catch is high in calcium, iron, and zinc, and relatively lower in omega-3 fatty acids than other cases, despite the prevalence of small pelagics (Figure 7b). This reflects the nutrient composition of usipa, the dominant species by volume (Figure 7c). Among other major species, utaka is a good source of all the nutrients studied here, including relatively high levels of vitamin A. Ndunduma, a small pelagic species which has largely replaced large-scale landings of chambo, is generally more nutritious than chambo except for lower levels of zinc (Figure 7c). Here, it is notable that the nutrient profile of chambo is very different from that of the small pelagic species, particularly usipa, which is especially high in calcium (more than 120% child RNI per 100g serving versus about 1% child RNI equivalent provided by a 100g serving of chambo).

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Figure 7: Nutrient yield and allocations for Malawi. a) Past catch in Malawi from the Food and Agriculture Organization, by fishery sector. Small-scale fishery catch data not available prior to 2007. b) Total nutrient yield from catch in 2017, expressed in terms of Recommended Nutrient Intake (RNI) equivalents for children aged 7 months-6 years. Colors represent species (refer to panel a). c) Nutrient content of most caught species by volume, in terms of % daily child RNIs met by consuming a 100g edible portion. Species are ordered by overall most nutrient-dense to least, calculated as the sum of the bars. d) Nutrient yield from chambo and usipa (primary species) allocated to coastal (within 25km of the coast) and inland populations. Data from market surveys. e) Nutrient yield from chambo and usipa allocated to rural and urban populations. Data from market surveys.

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3.5.3 Nutritional upsides and downsides (net nutritional yields) of various allocation drivers

Small-scale fisheries account for the vast majority (98.4%) of Malawi's catch by volume, and provide similar proportions of nutrient yield, ranging from 98% of vitamin A to 99.3% of iron.

When comparing two species, chambo and usipa, in terms of the flows of nutrients from those fisheries to either coastal (<25km from Lake Malawi) or inland (>25km from Lake Malawi) market destinations, coastal nutrients are provided overwhelmingly by usipa, with almost 100 percent of nutrients from chambo destined for inland markets (Figure 7d). In addition, 33% of nutrients from usipa are available to rural consumers, whereas only 17% of nutrients from chambo are available to rural consumers (Figure 7e).

4. Discussion

Effectively addressing the world's pressing food systems challenges requires not only reacting to present issues but also proactively designing approaches that anticipate future conditions of the world's social and natural systems. In this paper, we have introduced and applied a methodological approach for considering the prospects - and limitations - of governing fisheries for nutrition in the context of climate change. Like all models, the fisheries models that we used contain error and uncertainties from data limitations and model assumptions. Nonetheless, the results indicate that the effect of different governance approaches is likely to vary substantially from place to place. This finding is broadly consistent with most work on fisheries and climate change, which anticipates that some of the worst climate impacts will be experienced in low latitude countries (Cheung et al. 2023; Golden et al. 2016). The implications for availability of nutrients for countries and target subnational populations depend jointly on the predicted impacts of climate change, the potential for increasing fishery yield over time from sustainable management, the nutrient content of targeted species, the variety of post-harvest processes that shape the physical and economic accessibility of available nutrients, and the governance approaches that are applied from production through processing and distribution.

For some of the case study countries, investment in improved fisheries management produces substantial nutritional upsides, which could potentially counteract predicted nutrient losses due to climate change and BAU fishing mortality. In both Peru and Chile, excluding anchoveta (which is not commonly consumed locally and which is largely used for fishmeal/fishoil), climate change could substantially threaten fisheries production without climate-adaptive management interventions, whereas adopting a climate-adaptive management approach indicates increases in nutrient yield by mid-century relative to today. For these countries, prioritizing fisheries management interventions, such as regularly re-evaluating catch limits or other means for controlling fishing mortality (e.g., input-based effort controls) and promoting international cooperation for transboundary fish stocks and avoiding illegal, unreported, and unregulated fishing, may represent a priority for securing future nutrition provisioning from aquatic foods.

Further, this analytical approach can illuminate nutrient-rich species to prioritize both for fisheries management and allocation decisions (Bennett et al. 2021). For example, in many of the examined national allocative drivers, the management and flows of small pelagic fish (e.g., anchoveta in Peru and Chile, *Sardinella spp*. and *Ethmalosa fimbriata* in Sierra Leone, *Engraulicypris sardella* in Malawi) heavily influence nutrient yield outcomes. Small pelagics have been shown to be among the most nutritionally-dense as well as affordable options in many countries (Isaacs, 2016; Robinson et al., 2022b), and thus represent potential priority species for nutrient-sensitive fisheries management, supply chain interventions, or educational initiatives or incentives to increase direct human consumption.

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In other contexts, notably Sierra Leone within the cases we examined, projected climate impacts are alarming, and climate-adaptive management interventions may provide little recourse. We re-emphasize that the bioeconomic model used here is based on global data and does not fully account for context-specific dynamics, and is best approached as a means of exploring future scenarios, not a specific planning tool. Nevertheless, the general direction and projected trends for tropical coastal nations, particularly in West Africa, point to serious potential nutritional losses from fisheries due to climate change (Cheung et al. 2023; Golden et al. 2016). In these cases, decision makers may consider compensating elsewhere in national food systems and nutrition policy, with particular attention to planning for subpopulations currently dependent on fish. This could entail supplementing aquatic foods supply with aquaculture and imported fish, alongside additional terrestrial food sources. Additionally, decision makers might examine allocative drivers including exports and foreign fishing alongside alternate nutrition sources. More broadly, these sobering results underscore the humanitarian and ecological imperatives for bold and concerted global action to reduce greenhouse gas emissions.

This approach can also illustrate where allocative drivers in the midstream of value chains (processing and trade) may be as or more important than climate-adaptive fisheries management in mediating nutrient availability. Indonesia represents a case where climate impacts may not be as severe as in other countries under this set of projection models and scenarios, climate-adaptive management represents a less significant lever, and national allocative levers including foreign fishing and exports may have less of an impact. Here, subnational allocation policies could be prioritized instead. In Sierra Leone, exports provide a striking example of how a policy driver that may appear modest by overall volume (~13%) could merit further consideration as a nutritional intervention because it diverts up to 40% of the yield of critical micronutrients for which the majority of Sierra Leone's population faces deficiencies. In Peru and Chile, the majority of nutrients from both anchoveta and non-anchoveta fisheries are exported.

Of course, the relationship between exports and nutrition outcomes is complex; fish exports do not necessarily mean a net nutrition loss for domestic populations if revenue is directed toward other nutritious foods (e.g., Fabinyi et al., 2017; HLPE, 2014) including fish (Béné et al. 2010; Asche et al. 2015) and livelihoods linked to export markets enhance food purchasing power for households. At the same time, in many contexts, globalization and trade of traditionally-consumed fish has led to food system transitions toward highly processed foods, creating poor ecological and nutritional outcomes (Golden et al., 2021b). Power dynamics in fisheries export markets can concentrate benefits among larger firms to the detriment of small-scale fishers and fish traders (e.g., Nunan et al., 2020; Arthur et al., 2022). Further, high nutrition exports may be the consequence of limited domestic demand and/or high foreign demand for certain species, as well as substitution or competition from aquaculture production. However, these market forces are shaped, in part, by governance decisions. For example, in Peru, public campaigns substantially increased domestic demand for anchoveta, but the impacts were limited and short-lived due to structural factors including differential regulations for industrial and artisanal fleets and post-harvest value chain dynamics limiting cost-effectiveness of processing anchoveta for human consumption (Majluf et al. 2017). Of course, exports often supply needed nutrients to external populations, as is the case, for example, with regional trade within Africa (Béné et al. 2010; Mussa et al. 2017). Thus, applications of this analytical approach should carefully define target populations and while also considering tradeoffs between income and direct nutrient provisioning and between different target and non-target populations. Nuanced understandings of demand and consumption dynamics, and the broader economic context, would be needed to develop policies to address exports as a potential driver of nutrition yield loss.

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None of the cases had complete and comprehensive data to assess all drivers evaluated in the analytical approach. However, our approach underscores the idea that the absence of perfect data does not preclude any examination of nutritional dimensions of fisheries management. Furthermore, the method indicates where additional data collection could illuminate the impact of other drivers. In all cases except for Malawi, greater investigation of subnational allocation and distribution would be needed to better understand access to aquatic foods nutrients within each country and to craft effective policies. There may be economic and nutritional tradeoffs from changes to these drivers (including income derived from foreign fishing, exports, and conversion to fishmeal/fish oil) that are not explored here. Further, using more country-specific and subnational data could reveal additional drivers in aquatic food systems, such as changing demand or preference for particular kinds of products in certain places, which in addition to climate change, is likely to affect the contributions of aquatic and other foods in diets (Naylor et al. 2021). In subnational studies, analysts could also incorporate or prioritize different sets of nutrients for fisheries management and allocation decisions, depending on the specific nutrient needs or deficits within target countries or subpopulations, and the nutrients provided by locally-available aquatic foods (Koehn et al. 2023). For example, Indonesia's fisheries are uniquely rich in vitamin A, and 85% of the population faces vitamin A deficiencies. This points to priority areas for further study, such as the subnational flows of and barriers to access to vitamin A-rich species such as snappers. Interventions, such as socio-technical bundles (e.g., enhancing market infrastructure and processing technologies to reduce loss, reducing transport and transfer costs to target markets, supporting fisher and trader organizations, developing information and communication technologies to connect traders to target markets), nutritional interventions such as development of fish powder for young children and inclusion of fish in school feeding programs, and subsidies for aquatic foods can increase the distribution and availability of aquatic food nutrients to target populations.

Similarly, more nuanced subnational investigation could contextualize the notable result that, except for Malawi, large or industrial scale fisheries tended to disproportionately contribute to nutrient yields relative to catch volumes. This could indicate that smaller-scale fisheries may not have access to more nutritious fish, which could be due to regulatory, cultural, or logistical factors (e.g., more nutritious pelagic fish may be further from shore). It may also be that the full diversity of species caught and consumed from small-scale fisheries are not well-represented in global datasets, in particular if they do not enter formal markets or tracking systems. Globally, small-scale fisheries tend to provide more fish for human consumption (Teh & Pauly, 2018; FAO, 2020), so if these patterns hold true across other regions, these results could indicate that more nutritious fish caught in large-scale fisheries are less available to meet local population nutrient needs. Further, subnational investigation of how fish from large- vs. small-scale fisheries are allocated to export markets and non-food uses could reveal how policies governing species and catch allocation between large- and small-scale fishery sectors ultimately impact nutrient availability to vulnerable populations.

In addition to contextualizing findings from this analytical approach, use of finer-scale data could avoid potential inaccuracies or mismatches that may stem from the use of coarse global-level data and models. For example, the predictive nutrient model for finfish embeds assumptions about what constitutes an "edible" portion of each species that may not be universal across cultures and contexts. Similarly, the climate-linked bioeconomic model projections were intended to explore broad relative changes in fisheries outcomes under different policy scenarios, so the fishing mortality assumptions underlying the No Adaptation scenario do not necessarily reflect actual fisheries management interventions for particular species in these national case studies, nor is the climate-adaptive management scenario necessarily achievable or appropriate. Further, because the No Adaptation

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scenario assumes a fixed level of fishing mortality that is highly uncertain and may not represent current fishing levels in each country, the differences between the Full Adaptation and No Adaptation scenarios may be inflated. There is also inherent model imprecision due to data limitations, e.g., catch-only stock models of data-limited stocks (Ovando et al., 2022), and temperature-only climate projections (McHenry et al., 2019). Given that almost any empirical application of this analytical approach will suffer from similar limitations and uncertainties, its most appropriate application is in the construction of future scenarios as a basis for considering the range of interventions that could have a meaningful impact on nutrients available from aquatic foods. Specific interventions could then be explored using species- and region-specific models and downscaled climate projections where available.

5. Conclusion

This modeling exercise, while representing imperfect data and requiring several assumptions, suggests that the effectiveness of different types of policies to maintain or enhance nutrients available to domestic populations from fisheries operating in national waters varies substantially among countries. Where climate change limits potential nutrient upsides of fisheries management, alternative policy approaches might be necessary, including those that have the potential to increase the proportion of nutrients available for consumption by communities who need them the most, or that enhance profits from fisheries and thereby enable purchase of other aquatic food sources (e.g., aquaculture, imported aquatic foods) or alternative nutrient-dense foods. In some countries, there may be underdeveloped or emerging fisheries with untapped nutrient potential that could allow for a shift to alternative species to meet specific nutrient needs.

Within the realm of fishery management, this analytical approach provides insights for decision-makers considering how to maintain or increase access to nutrition provided by fisheries for the domestic population. This might be considered alongside other objectives including economic returns, employment, and social objectives; all of these could incur trade-offs. This approach may also help assess the costs of public health investments within the fisheries sector. For example, decision makers might weigh the costs of fisheries management against the benefits of having healthy children who can develop their full potential and contribute to society as well as the costs of investment in public health due to anemia, malnutrition and other diseases associated with poor nutrition. By quantifying nutrient yield from fisheries, disaggregating yield into specific micronutrients beyond protein, and considering the complex dynamics of trade and foreign catch, we provide a more complete picture–albeit in broad strokes–of the benefits of managing fisheries for nutrient provisioning. By applying this approach with finer details including country or region-specific data sources, or relevant and feasible management frameworks, decision-makers could better evaluate tradeoffs and compare policies to achieve multiple fisheries goals.

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