

Spatial Footprint and Climate Risk in Fishmeal and Fish Oil Production

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Lauren Ashley Shea

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the thesis entitled:

Spatial Footprint and Climate Risk in Fishmeal and Fish Oil Production

Submitted by Lauren Ashley Shea in partial fulfillment of the requirements for the degree of

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Oceans and Fisheries

Examining Committee:

U. Rashid Sumaila, Professor, Institute for the Oceans and Fisheries, UBC
Supervisor

Daniel Pauly, Professor, Institute for the Oceans and Fisheries, UBC
Supervisory Committee Member

Philippe Le Billon, Professor, School of Public Policy and Global Affairs, UBC
Additional Examiner

Additional Supervisory Committee Members

Colette Wabnitz, Research Associate, Institute for the Oceans and Fisheries, UBC
Supervisory Committee Member

William Cheung, Professor, Director, Institute for the Oceans and Fisheries, UBC
Supervisory Committee Member

Abstract

Fishmeal and fish oil (FMFO) are essential components for compound aquatic feeds supporting the fed aquaculture sector, yet their use is controversial. This controversy centers on the utilization of wild fish to feed farmed fish and whether reducing whole fish into flour and oil is the best use of wild fish populations, especially given that the species targeted for FMFO production, mainly small pelagics, play a crucial role in marine food webs and underpin nutrition security for many people worldwide. This controversy is exacerbated by rapid changes in the ocean, driven by climate change. Despite the world's largest fishery (by weight) being mostly reduced into FMFO, publicly available data on the industry are scarce. This thesis addresses two main questions, 1) what is the global footprint of the FMFO industry, and 2) how will climate change impact the industry?

To map the spatial distribution of the FMFO industry, I identified factories in countries producing at least 500 tonnes of fish oil in 2022 (n=63), uncovering 506 factories owned and/or operated by 413 companies. Data on raw materials used to produce FMFO revealed that while most factories utilize fish by-products, many still rely on whole fish. This information has been compiled into an open-source database including company names, factory locations, and raw materials.

Building on this, I analyzed projected maximum catch potential (MCPs) for species reduced as whole fish (n=32) under two contrasting climate scenarios: high-emission and low-emission. Findings suggest high variability in projected MCPs across the different species and Exclusive Economic Zones (EEZs) in which they are caught under both climate scenarios. Summarized by

continent, aggregate MCP is projected to decline by the mid- 21st century off the coast of Africa, Asia, Europe, with South America experiencing the greatest declines.

The findings from this thesis underscore the critical importance of understanding where FMFO production is concentrated to inform the development of cooperative national and international policies promoting environmentally and socially responsible standards for the FMFO industry. Additionally, understanding the impact of climate change on species exploited for FMFO production is crucial for developing more adaptive and sustainable fisheries management practices.

Lay Summary

Farming animals for food, once seen as a solution to over-exploitation, can be at odds with sustainability. An example is the use of wild fish to feed farmed animals like pigs, chickens, and fish. For optimal growth and development, farmed fish often rely on fishmeal and fish oil (FMFO) in their feed. FMFO is mainly produced from whole, wild, small fish, like anchovies and sardines. Unfortunately, this industry often lacks transparency and is data poor. To fill data gaps, this thesis provides a first look at mapping the spatial distribution of FMFO factories and exploring how climate change might affect the populations and fisheries that support this industry. This information is critical to inform the development of more adaptive fisheries management and fair and sustainable resource policies.

Preface

This thesis contains my own original work, which has benefited from the contributions of several colleagues. My supervisor, Dr. Sumaila, helped me develop the research questions, methods, and data analysis deployed in Chapter 2, “The spatial distribution of the fishmeal and fish oil factories around the globe”. Dr. Sumaila and Dr. Wabnitz provided substantive feedback during the writing process. Dr. Cheung and Dr. Pauly also provided valuable feedback during the writing and final editing of this chapter, as well as, advising on preparing the chapter for journal submission. A version of Chapter 2 has been submitted for publication and is currently under evaluation. All of my committee members, Dr. Wabnitz, Dr. Cheung, Dr. Pauly, and Dr. Sumaila, are co-authors on this paper.

The research questions and methods in Chapter 3 were developed with the guidance of Dr. Sumaila, Dr. Cheung, and Dr. Wabnitz. The data analysis was carried out with the help of Isabella Morgante, a PhD candidate at the Institute for the Oceans and Fisheries. Isabella extracted the data for fish species of interest using the dynamic bioclimatic envelope model (DBEM) developed by the Changing Oceans Research Unit at IOF. She also advised on script writing in R studio. I received valuable feedback on the writing in Chapter 3 from all of my committee members and am grateful for their comments throughout the development of this chapter. A version of my third chapter, “Climate change impacts on the FMFO industry”, will be expanded upon with a climate vulnerability assessment and submitted to an academic journal for publication. Co-authors on this paper include Dr. Sumaila, Dr. Wabnitz, Dr. Cheung, Dr. Pauly, and Miss Morgante.

Chapters 2 and 3 were prepared as independent articles and therefore may have repetitive introductory sections.

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List of Abbreviations

EEZ – Exclusive Economic Zone

ENSO – El Niño Southern Oscillation

ESM – Earth System Model

FMFO – Fishmeal and Fish Oil

IFFO – The Marine Ingredients Organization (previously the International Fishmeal and Fish oil Organization)

IMROP – Institut Mauritanien de Recherche Océanographique et des Pêches

MCP – Maximum Catch Potential

MSY – Maximum Sustainable Yield

NPP – Net Primary Productivity

RCP – Representative Concentration Pathways

SOFIA – State of the World Fisheries and Aquaculture

SSP – Shared Socioeconomic Pathways

Acknowledgements

I would like to thank my supervisor, Dr. Sumaila, for responding to my lengthy email that I sent to him while I was anchored in the Republic of Palau, and for inviting me to join his research lab at the Institute for the Oceans and Fisheries. He has been supportive and encouraging from start to finish and I have learned a lot from him. I would like to thank Dr. Wabnitz, who has been a valuable mentor and friend to me since I first joined UBC. She is compassionate and listens deeply, and I truly appreciate her guidance. Thanks are also due to my two other committee members, Dr. Cheung and Dr. Pauly, who have provided valuable feedback and fresh ideas along the way.

Secondly, I want to thank the team at the Stimson Center and China Dialogue (now Earth Dialogue) for inviting me to participate in a workshop in The Gambia early on in my studies and allowing me to contribute to the writing of the report, “Charting a Blue Future for Cooperation between West Africa and China on Sustainable Fisheries” (2023). There I met many wonderful people, like Mustapha Manneh, who guided me through fish markets and fishing communities and shared their personal stories relating to the fishmeal industry in their country. I learned a lot during this trip and have a deep respect for those who are on the ground standing up for their communities and environment.

I want to acknowledge the support I received from the Packard Foundation during my second year of studies. I am grateful for all that I learnt while engaging in projects with their team. I appreciate the staff at IFFO: The Marine Ingredients Organization for providing data on global FMFO production and prices, as well as, Dr. Patricia Majluf for the data she shared on the FMFO factories located in Peru.

I am incredibly grateful for my friend and colleague, Izzy, who has been a close friend since Week 1 of our graduate school journey. I appreciate her friendship more than anything, but also the patience and guidance she offered during my data analyses. I would also like to thank my rowing teammates, Noelle, Chantale, and Isabelle, all of whom supported me since the beginning of this process and rowed across the Atlantic Ocean with me in the middle of my degree. If it weren't for their encouragement, I might still be at sea rather than finishing my degree.

I want to thank my partner, Tim, who encouraged me every single day of this process and continues to help me find a way through life's challenges.

Finally, I want to acknowledge that the work undertaken for this thesis took place on the unceded and traditional lands of the ʷməθkʷəy̓əm (Musqueam), Skwxwú7mesh (Squamish), səliłwətał (Tsleil-Waututh), ləkʷəŋən (Lkwungen), ƳSÁNEĆ (Saanich) and peoples.

1. Introduction

“Man wants to see nature and evolution as separate from human activities. There is the natural world, and there is man. But man also belongs to the natural world. If he is a ferocious predator, that too is a part of evolution. If cod and haddock and other species cannot survive because man kills them, something more adaptable will take their place. Nature, the ultimate pragmatist, doggedly searches for something that works. But as the cockroach demonstrates, what works best in nature does not always appeal to us.”

–Mark Kurlansky,
“Cod”, 1997

Problem Statement

Fishmeal and fish oil (FMFO) are critical inputs for animal feeds, but their production often relies on whole, edible wild fish. The reduction of wild fish into feed ingredients for farmed animals has caused concerns regarding fisheries sustainability (Shannon and Waller, 2021), food and nutrition security (Majluf et al., 2017), and waste pollution (Liu and Sumaila, 2010).

Although novel ingredients have been developed to replace FMFO, they have so far lacked scalability and uptake (Cottrell et al., 2020). To better understand the landscape of the FMFO industry, this study addresses gaps in the literature regarding the global spatial distribution of FMFO factories and the raw materials they use for FMFO production. It then, explores the projected impacts of climate change on each of the key species reduced into FMFO.

Research Objectives

The overall goal of this thesis is to provide information on the FMFO industry to better understand its footprint and current state, with a view to inform more equitable and sustainable fisheries management policies. To achieve this goal the thesis has three specific objectives:

1. Identify and map the spatial distribution of FMFO factories around the world and identify areas of high factory concentrations (hotspots);

2. Create a publicly-available database that includes FMFO factory locations, names of the companies who own the factories, and the types of raw materials used for FMFO production; and
3. Analyze the projected climate change impacts on the small pelagic (forage fish) species used as whole fish (as opposed to fish by-products) for FMFO production.

Background and Literature Review

Fisheries have long been an important source of food and are some of the last wild foods harvested at large scale. Although the global marine fisheries catch has peaked in the mid-1990s (Pauly and Zeller, 2016), the demand for marine and other aquatic resources has continued to increase (Hasan and Halwart, 2009), with aquatic products being one of the most traded food commodities worldwide (Bellmann et al., 2016; FAO, 2024). Global aquaculture now makes up a significant proportion of production, reaching 130.9 million tonnes in 2022, accounting for 59% of global fisheries and aquaculture production (FAO, 2024). While aquaculture has played a significant role in meeting global demand, many studies have raised sustainability concerns associated with the sector (Arnason, 2005; Belton et al., 2020; Naylor et al., 2021; Sumaila et al., 2022). A critical issue is the use of FMFO in feeds for farmed (aquatic) species.

FMFO are co-products derived from the processing of raw material (fish) into its basic nutritional components. While the manufacturing process may vary, the main production process involves heating and pressing fish and separating the resulting products into solids and liquids (information summarized from FAO (1986); Figure 1-1). The liquids, made up of oil and water, are then separated and the oil is refined into fish oil, while the water is evaporated into a

concentrate of fish solubles. The solids are dried and ground into powder (fishmeal). The raw materials for FMFO can be derived from whole fish, fish by-products, or both.

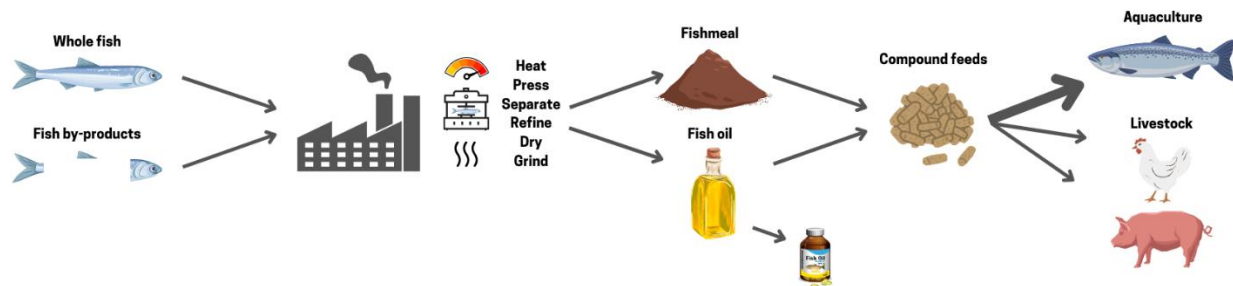


Figure 1-1 A simplified depiction of FMFO production.

Historical context of FMFO industry

Historically, prior to aquaculture's domination of the FMFO market, fishmeal was used as fertilizer for terrestrial crops and feed for livestock (Froehlich et al., 2018). By the late nineteenth century, global livestock production increased rapidly and by the early twenty-first century, over half of the world's agricultural land was used for pasture (Wintersteen, 2021). Although ruminants (i.e., cows and sheep), which have a digestive system that has evolved to survive on grasses, and don't require high-protein feeds, monogastric animals (i.e., pigs and chickens) require specific amino acids in their diets (Wintersteen, 2021). Feeds became the largest expenditure for farmers, and the rapidly industrializing world needed cheap protein (Wintersteen, 2021).

The oceans were an excellent source to turn to. Small pelagic fisheries, also known as forage fisheries, focused on species like sardine and anchovy, were extremely productive and already being caught for canning (Pikitch et al., 2014). Fishmeal offered a profitable market for cannery

by-products and surplus catch. In other parts of the world, small pelagics like menhaden were considered inedible due to their small size and bony fillets, and FMFO created a market for these abundant fisheries (Kurlansky, 1997). By the twentieth century, fishmeal had become a global commodity heavily relied upon by agriculture (Wintersteen, 2021). In 1960, fishmeal was almost exclusively used for pig and poultry production, while fish oil was used for pet foods, biofuel, and cooking fuel (FAO, 2024). However, starting in 1980, the aquaculture industry began utilizing these products and as the industry grew, so too did its consumption of FMFO. By 2021, aquaculture consumed over 87% of fishmeal and 74% of fish oil (FAO, 2024), driving up prices as supply plateaued (Figure 1-2).

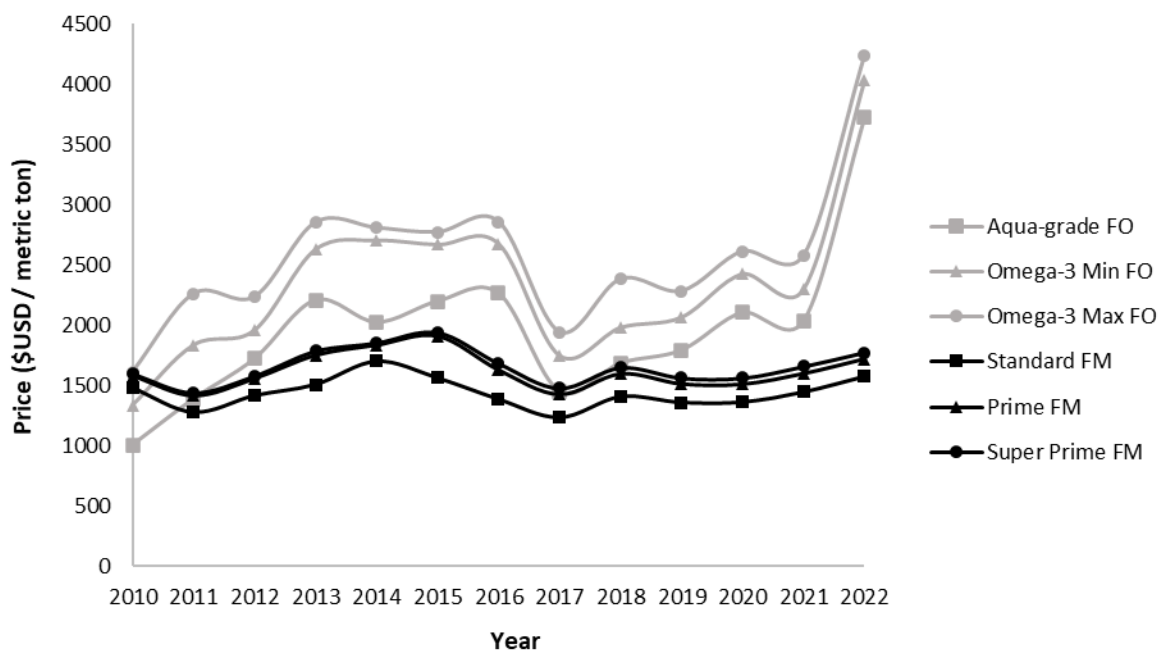


Figure 1-2 Fishmeal (FM) and fish oil (FO) prices in USD from 2010-2022. Data provided by IFFO: The Marine Ingredients Organization.

To cope with limited supply and high prices, FMFO is incorporated into compound aquatic feeds. While inclusion rates have declined due to improved feeding efficiency and alternative protein sources becoming available, demand for FMFO remains high due to the large proportion of carnivorous species being cultivated (FAO, 2024; Hasan and Halwart, 2009) and their need for essential nutrients (Tacon and Metian, 2015). Fishmeal is valued for its high protein content, complete amino acid profile, and high nutrient digestibility, while fish oil contains essential fatty acids necessary for growth (Bendiksen et al., 2011; Hall, 2010). Despite significant research into FMFO alternatives (Bandara, 2018; Cottrell et al., 2020; Nagappan et al., 2021), challenges remain in finding replacements that do not compromise the health, immunity, and growth of fed aquaculture species (Egerton et al., 2020; Zhou et al., 2018).

Sustainability concerns of FMFO industry

A major sustainability issue in aquaculture is the use of whole fish for FMFO production. Currently, 66% of fishmeal and 47% of fish oil come from whole fish, primarily small pelagics (FAO, 2024). However, as mentioned above, these fish have been reduced into FMFO for decades, supporting terrestrial livestock production. So, why the present concern about this practice?

There are multiple reasons to be concerned for the reduction of whole fish to FMFO. Fisheries production has plateaued or declined and it was estimated that in 2021, 38% of fisheries were considered overfished (FAO, 2024). The modern fishing fleet of today is strong enough to take all that it wants and the oceans are no longer considered “inexhaustible” in the way they once were. This is causing fisheries managers and stakeholders to reevaluate how fisheries resources are currently being used and if that purpose is for the greatest benefit. Here we explore three

sustainability challenges that the FMFO industry faces, globalization, food security, and climate change.

Globalization of the industry

With the globalization of the FMFO industry making it possible to source FMFO from marine areas across the globe, trade has undermined the industry's incentives to respond to environmental and social feedback regarding capacity of different regions to supply fish (Deutsch et al., 2007). Government practices and policies often facilitate and drive the development of the FMFO and aquaculture industry without the implementation of environmental policies meant to manage it concurrently (Deutsch et al., 2007; Eagle et al., 2004). This has contributed to a “stretched” production chain, not only across larger geographical distances, but also increased agents involved in the supply chain, making the entire system more complex and difficult to manage (Deutsch et al., 2007; Lebel et al., 2002). FMFO trade data does not provide detailed information regarding fish species' names or sources, and this information is critical for better management of the industry.

Food security implications

The de-coupling of the FMFO supply chain from the social-ecological systems of which the fish (raw material) originates can also mask issues regarding food and nutrition security for local communities (Deutsch et al., 2007) near to factories. Many small to medium pelagic fish stocks that are currently exploited for FMFO are also an important source of food and nutrition for nations around the globe (Bavinck et al., 2023; Christensen et al., 2014), some of which are already food insecure. For example, in West Africa, small pelagics, like *Sardinella* spp., represent a critical source of affordable nutrition (Ba et al., 2017; Failler, 2014). However, in recent years,

much of the catch in small pelagics, e.g., Round sardinella, Bonga shad, and Horse mackerel, has been redirected towards FMFO production, diverting fish away from local fish processors, often women, and local households, accelerating over-exploitation, and leading to rising prices (Gorez, 2018). This competition for fish resources is being further threatened by climate change (Sarre et al., 2024).

Climate change and fisheries

Climate change is exacerbating the extractive pressure on small pelagic fisheries as changing environmental conditions, such as rising temperatures, are forcing fish to move, impacting fish abundance globally (Cheung et al., 2010; Palacios-Abrantes et al., 2022). Environmental changes are especially problematic for small pelagics who are highly responsive to environmental fluctuations (Alder et al., 2008; Sarre et al., 2024), like El Niño events. For example, Peruvian anchoveta, which supports the largest fishery in the world and a major source of fish for FMFO, has collapsed several times due to El Niño events, made worse by overfishing (Pauly, 2006). Climate change is expected to further impact the anchovy fishery negatively (Oliveros-Ramos et al., 2021; Salvatteci et al., 2022), and consequently the FMFO industry as a whole.

Thesis outline

In an effort to inform the current debate and stakeholders involved in developing and implementing more effective management and governance practices for the FMFO industry, this thesis addresses two key issues. First, the lack of publicly-available information regarding the spatial distribution of this industry. Second, the impacts of climate change on the main species used in FMFO production. Findings from this thesis are aimed at providing some of the

information needed to make more sustainable and equitable decisions regarding the use of global fisheries resources.

My thesis consists of four chapters, beginning with this introduction. The second and third chapters address each of the research questions and the final chapter discusses limitations, opportunities for further study, and policy recommendations based on the information learned.

2. The Spatial Distribution of the Fishmeal and Fish Oil Factories Around the Globe

Introduction

Wild fisheries catch is declining, and much hope is pinned on the aquaculture industry to meet growing seafood demand (Sumaila et al., 2022). However, many of the species that are produced and considered desirable by people in high-income countries are carnivorous, i.e., approximately 63 million tonnes (t) in 2020 (FAO, 2022), and need to be fed. To meet fish nutrition requirements, aquatic feeds often contain fishmeal and fish oil (FMFO) ingredients (Egerton et al., 2020). FAO (2022) reported in its bi-annual ‘State of World Fisheries and Aquaculture’ (SOFIA) that 86% of FM and 73% of FO was directed towards aquaculture. And while the supply of FMFO has plateaued, the price of FMFO has grown as demand has increased (Truong et al., 2023).

FMFO can be produced using whole fish and/or fish processing waste (e.g., heads and tails from canning operations). However, to date, a large proportion of raw materials for FM (66%) and FO (47%) still originate from wild capture, small pelagic fisheries (FAO, 2024) – the so-called forage fisheries (Pikitch et al., 2014). This practice is controversial for three main reasons. First, capturing fish to produce aquaculture feed threatens marine ecosystems by, for instance, increasing demand for fishing on wild fish populations that could exacerbate overfishing (Froehlich et al., 2018; Pikitch et al., 2014). Second, diverting wild fish from human consumption to feed aquaculture undermines human food and nutrition security of low-income people all over the world (Cashion et al., 2017; Majluf et al., 2017; Willer et al., 2024). Third, the globalization of FMFO trade has resulted in lower traceability of aquatic feed inputs (Naylor

et al., 2009). This points to an important question raised by Naylor et al. (2009): “How should forage fish resources be allocated among competing uses: to the highest economic value (e.g., ranched bluefin tuna), to feeding the largest number of people, or to conserving natural ecosystems?”

FMFO are critical to the fed aquaculture sector due to their unique nutrients and high protein content, which are required to grow fish to market size. Fishmeal is particularly rich in protein, with a much higher protein to meal ratio compared to plant-based alternatives (Hussain et al., 2024). Moreover, plant-based proteins, like soybean meal, may contain antinutritional factors that negatively affect the intestinal microbiota and immunity of carnivorous aquaculture species, further limiting the ability to fully replace fishmeal with vegetable proteins (Zhou et al., 2018). Aquaculture species can also have significantly higher lipid requirements than terrestrial farm animals. Fish oil, which contains high levels of key lipid classes including omega-3 long-chain poly unsaturated fatty acids (Eicosapentaenoic acid (EPA) and Docosahexaenoic acid (DHA)), is essential for the growth and nutrition of fish and must be included in a fish’s diet as they cannot synthesize these fatty acids themselves (Colombo, 2014; Truong et al., 2023).

Many of the nutrients essential for fed aquaculture and driving demand for FMFO are also important for humans. Small pelagic fishes are a vital source of affordable nutrition in many coastal emerging economies, like those in West Africa and South East Asia (Bavinck et al., 2023). Notably, one study found that if Peruvian anchovy (*Engraulis ringens*), the largest fishery by weight in the world, were directed towards direct human consumption rather than FMFO production it could eradicate severe malnutrition in children globally (Majluf et al., 2017). Omega-3 fatty acids specifically are also important for various human bodily functions,

including anti-inflammatory processes, brain function and development, and heart health (Surette, 2008). Similar to fish, humans cannot synthesize EPA and DHA, and they must be obtained through diet (or supplements) (Surette, 2008).

While studies have addressed the efficacy of using whole fish for FMFO production and how this production should be prioritized (Bavinck et al., 2023; Cashion et al., 2017; Cottrell et al., 2020; Froehlich et al., 2018), there has been limited research on the production plants themselves (Tung et al., 2023). Available reports document their negative environmental and socio-economic impacts (Summers, 2019; *The Human Cost of Overfishing*, 2023; Thiao and Bunting, 2022). The cooking and drying of fish during FMFO production generates substantial emissions of particulate matter, nitrogen oxides, sulphur oxides, and hydrogen sulfides, as well as high odor levels from excess trimethylamines (Muñoz, 2020). One recent report by The Changing Markets Foundation documented numerous accounts of pollution and environmental degradation in Peru's FMFO industry, including untreated wastewater dumping and decreased air quality (Changing Markets Foundation, 2020).

With the aquaculture sector projected to expand, and despite an increase and focus on non-fed aquaculture, demand for FMFO will continue. To address sustainability, equity, and conservation concerns associated with this industry, it is essential to develop robust policies for its effective governance and management. To support such efforts, an understanding of the industry's landscape, challenges, and opportunities is key. This study maps the distribution of the FMFO industry, providing a critical first step in assessing the industry's global footprint and the potential impacts of individual production plants on neighboring communities. Such

foundational knowledge can also support informed policy-making and the promotion of more sustainable and equitable practices within the FMFO sector.

Methods

Our approach was informed by Clawson et al. (2022) and Oyinlola et al. (2018), two studies which investigated the spatial distribution of mariculture farms around the globe. The study covers all countries (n=63) that produced at least 500 t of fish oil in 2022, according to data provided by IFFO: The Marine Ingredients Organization (herein referred to as “IFFO”). The justification for focusing on these 63 countries is that they produced 99.8% of global fish oil supply in 2022.

FMFO production companies

We compiled the spatial database by first searching for FMFO production companies in each of the selected countries (n=63). Company names were found using national databases and membership associations (e.g., the European Fishmeal and Fish Oil Producers, IFFO, Marin Trust), peer-reviewed as well as grey literature, and online seafood business directories (e.g., www.trade-seafood.com). Country-specific data sources can be found in Table S1 of the Appendix.

IFFO is an international trade organization for marine ingredients (including FMFO). IFFO members account for 55% of FMFO world production and over 80% of FMFO traded globally (IFFO, 2024). Since this study focuses on production plants, rather than trade, only members listed as ‘Producers’ in the ‘Level’ column of the IFFO Members list were included in the dataset.

MarinTrust is a certification program for marine ingredient production factories that recognizes responsible fishery sourcing and production of marine ingredients (including FMFO) (Marin Trust, 2024). Companies fall under two international third-party MarinTrust certification standards: the Factory Standard (MarinTrust Standard), covering the “sourcing and production of marine ingredients at the factory”; and the Chain of Custody Standard, which “allows businesses in the supply chain (e.g., processors, packers, storage providers etc....) to be recognized for their use of MarinTrust certified ingredients”. MarinTrust also operates an Improver Program “dedicated to marine ingredient production factories involved in a Fishery Improvement Project”. All sites that met Factory Standard or were part of the Improver Program were included. The open-source certificates for these two categories were highly detailed and included the company name, site address, the species used for raw material, and whether the raw material was whole fish or by-products from other fish processing activities. Companies/sites that met the Chain of Custody Standard were only included if they were described as ‘Producing’ or ‘Processing’ FMFO. We did not include sites that only participated in trading, storage, distribution, packing, and/or packaging.

Once a list of FMFO-producing companies was compiled, we searched for company websites to find information regarding the number and location of production plants the company operated. If a company website could not be found, the production company was still included in the table, as long as it was listed as a producer of FM and/or FO by a membership association (e.g., IFFO, European Fishmeal and Fish Oil Producers (EFFOP)), a certification program (i.e., MarinTrust), a business and/or producer/supplier directory (e.g., trade-seafood.com), or a business account on a social networking platform (e.g., LinkedIn).

Locating FMFO production factories

Using the data collected above, we attempted to locate each company's factories and verify their location using the satellite image layer in Google Maps. Verification involved zooming in to the presumed location and checking that there was a factory building there (Figure 2-1). Once verified, the coordinates of the plant(s) were recorded.



Figure 2-1 Example of factory location verification using the Google Maps satellite layer. All factories had large warehouses and cylindrical tanks for FMFO processing and storage (highlighted in yellow boxes). Factories were typically located on the waterfront and clustered together in industrial zones.

If the company website and/or site address were not available, we searched the company name and country in the Google Maps search box to attempt to find the company's factories. In some cases, the factories could not be located due to the absence of a company's website, lack of information on the company's website, or factory addresses that could not be found on Google

Maps. When a factory address was provided but could not be pinpointed, we used an open-source geocoding platform (<https://geocode.xyz/>) to geocode the address. This platform also provided a confidence score between 0 and 1 for each geocode result. In instances where the city or province of the factory was provided, we used the geocode for that city or province.

Data types

We categorized the data compiled for FMFO factories into four data types based on our confidence level in each location (Table 2-1).

Table 2-1 Data types. Descriptions for the data types assigned to each unique FMFO factory.

Data Type	Description
A	Site location verified using the Google Maps satellite image layer. Factory address published on company website, provided by third-party source (e.g., Marin Trust certificate), or an active 'Business' pin on Google Maps.
B	Site address published on company website or by a third-party source but not verified using satellite image layer. Address was geocoded using the open-source geocode.xyz platform and the geocode confidence score was greater than 0.5.
C	The city or province in which the site is located is known and the coordinates for the city/province are used OR the geocode confidence score for the address is 0.5 or below (typically depicting that the address could only be matched to the city/province level).
D	Only the country in which the factory is located is known.

Raw materials

We also searched company websites and MarinTrust factory certificates for information regarding raw materials and production capacity for individual factories. We specifically wanted to know if the raw materials being used for FMFO were whole fish or by-products. More specific information regarding species and/or functional groups was included when available.

Global FMFO production

Global FMFO production data was provided by IFFO for the year 2022. This data guided our focus on specific countries during our search for FMFO factories and was used to calculate the FM to FO production ratio for each country (Table 2-2).

Table 2-2 Production of fishmeal and fish oil by country in 2022. FM = fishmeal; FO = fish oil. Data source for production quantities: IFFO.

Country	FM production (000 t)	FO production (000 t)	Ratio FM : FO	No. of factories
<i>Peru</i>	1003.36	100.33	10.0	126
<i>China</i>	400.46	56.07	7.1	22
<i>Chile</i>	378.60	150.93	2.5	33
<i>Vietnam</i>	352.06	179.00	2.0	16
<i>India</i>	347.17	63.45	5.5	23
<i>Thailand</i>	285.36	33.78	8.4	12
<i>USA</i>	237.70	87.84	2.7	14
<i>Japan</i>	202.50	68.58	3.0	3
<i>Norway</i>	184.72	126.69	1.5	17
<i>Morocco</i>	176.45	47.17	3.7	16
<i>Iceland</i>	162.60	68.80	2.4	10
<i>Denmark</i>	148.81	45.67	3.3	5
<i>Mexico</i>	135.00	29.89	4.5	11
<i>Russia</i>	129.61	6.70	19.4	2
<i>Ecuador</i>	117.75	14.90	7.9	18
<i>Mauritania</i>	91.95	21.32	4.3	42
<i>Faroe Islands</i>	65.88	24.76	2.7	1
<i>Brazil</i>	65.57	8.52	7.7	8
<i>Pakistan</i>	62.00	6.20	10.0	3
<i>South Africa</i>	60.39	11.35	5.3	5
<i>Myanmar</i>	50.00	6.50	7.7	4
<i>Indonesia</i>	49.28	4.73	10.4	11
<i>Spain</i>	46.35	10.42	4.4	6
<i>Oman</i>	45.22	8.19	5.5	5
<i>Philippines</i>	37.86	4.86	7.8	2
<i>Malaysia</i>	37.11	3.71	10.0	5
<i>New Zealand</i>	32.00	1.80	17.8	10
<i>Iran</i>	30.00	4.00	7.5	3
<i>UK</i>	22.73	7.95	2.9	5
<i>Germany</i>	22.52	13.15	1.7	2
<i>Turkey</i>	22.50	18.75	1.2	4
<i>Panama</i>	22.00	3.59	6.1	2

Country	FM production (000 t)	FO production (000 t)	Ratio FM : FO	No. of factories
<i>South Korea</i>	20.80	3.40	6.1	1
<i>Argentina</i>	18.44	0.90	20.5	4
<i>Taiwan</i>	18.00	0.70	25.7	1
<i>France</i>	17.71	9.92	1.8	6
<i>Latvia</i>	16.20	11.50	1.4	5
<i>Ireland</i>	14.08	2.08	6.8	2
<i>Lithuania</i>	12.50	1.80	6.9	1
<i>Estonia</i>	12.30	3.00	4.1	1
<i>Georgia</i>	12.00	10.00	1.2	1
<i>Portugal</i>	12.00	1.10	10.9	2
<i>Senegal</i>	11.50	2.50	4.6	2
<i>Poland</i>	10.75	7.50	1.4	1
<i>Mauritius</i>	10.55	0.90	11.7	1
<i>Australia</i>	8.25	3.09	2.7	5
<i>Papua New Guinea</i>	8.00	1.04	7.7	2
<i>Tunisia</i>	7.28	0.60	12.1	2
<i>Cameroon</i>	7.00	1.50	4.7	0
<i>El Salvador</i>	7.00	0.50	14.0	1
<i>Kazakhstan</i>	7.00	0.50	14.0	1
<i>Samoa</i>	6.50	0.85	7.7	1
<i>Namibia</i>	6.00	1.00	6.0	1
<i>Finland</i>	5.42	1.80	3.0	1
<i>Seychelles</i>	5.00	0.65	7.7	1
<i>Yemen</i>	4.50	1.00	4.5	4
<i>Canada</i>	4.45	4.18	1.1	7
<i>Gambia</i>	4.00	6.50	0.6	3
<i>Costa Rica</i>	3.00	1.00	3.0	1
<i>Belarus</i>	2.00	0.50	4.0	0
<i>Slovakia</i>	2.00	0.60	3.3	1
<i>UAE</i>	2.00	0.50	4.0	2
<i>Guinea</i>	0.00	1.50	0.0	0

FMFO factories and fed aquaculture production

Since fed aquaculture is the largest consumer of FMFO, we included global fed aquaculture production data from Clawson et al., 2022 in our study. We compared this data with global FMFO production data from the IFFO and factory location data collected in this study to better understand the interactions between these two industries.

Data analysis and visualization

Maps were created using QGIS version 3.4.8. Other data visualizations were made in R studio version 4.3.1.

Results

FMFO companies and their factories

We identified 506 individual FMFO factories located in 63 countries (Figure 2-2, Data S1—see Appendix). These factories are owned and/or operated by 413 companies. Of these, 63% had known locations verified using satellite imagery and company website information (data type A, Table 2-1). The remaining 37% were missing specific location information and/or could not be verified using satellite imagery (data types B, C, or D).

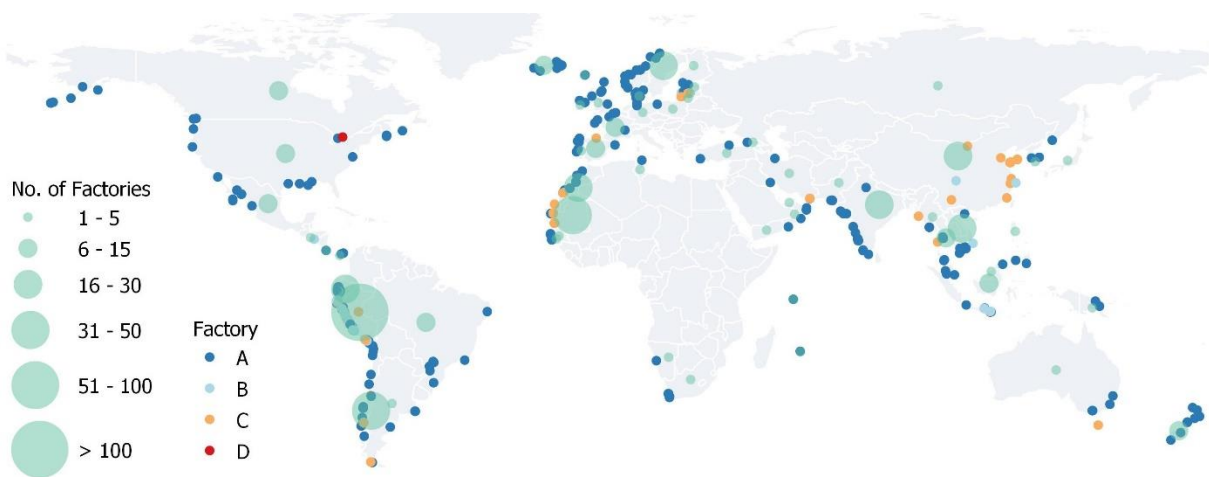


Figure 2-2 Spatial distribution of factories. Factories are color-coded by data type. Factories in dark blue (data type A) represent plants whose locations we were able to verify using satellite imagery and company website information. Green shaded circles represent and are scaled to the number of factories per producing country.

Peru had the highest number of FMFO factories ($n=125$), followed by Mauritania ($n=42$) and Chile ($n=33$). For both Peru and Mauritania, the national fisheries departments published lists of recognized FMFO factories with company names and site addresses, which greatly facilitated

their inclusion in our dataset. Only one other country, New Zealand, provided a similar published list of FMFO factories within its borders. Conversely, no company names or factory locations could be found for Belarus, Cameroon, and Guinea.

Most companies/factories were found using publicly available member lists from the IFFO and MarinTrust. The latter was particularly useful because company certificates were available for download and included the site address and detailed information regarding raw material inputs. Information on production capacity for individual plants was typically not available on company websites or national datasets, except for Peru.

Raw materials

Information on raw material inputs (i.e., whole fish or by-products) was available for 377 factories (75% of total). Species data, to the functional group level, was only available for 298 factories (59%). By-products were the most common single raw material used by factories (49%), with whole fish the primary source of raw material for 37% of factories (Figure 2-3A). The remaining factories (14%) used both whole fish and by-products. The majority of companies (60%) sourcing whole fish as raw material for FMFO production relied on small pelagics (<30 cm). By-products on the other hand were sourced from a greater diversity of species (Figure 2-4). By-products mostly originated from capture fisheries waste, but also included aquaculture waste (Figure 2-3B). It is important to note that these results do not account for production quantity due to limited available information.

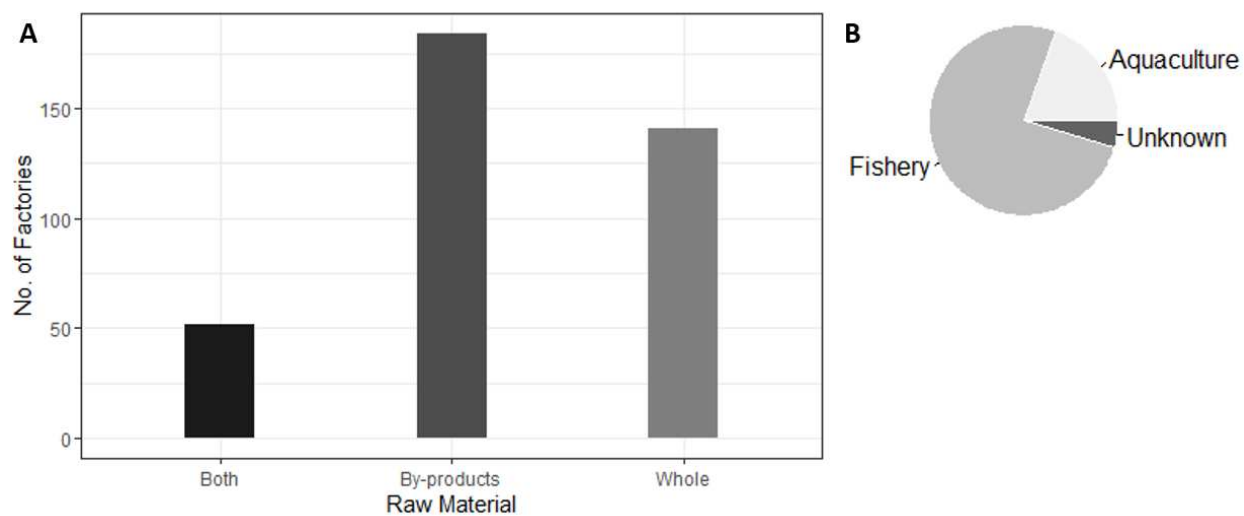


Figure 2-3 Source of raw materials used by factories to produce FMFO. (A) Number of factories using whole fish, by-products or both as raw materials. To avoid double-counting, factories that sourced whole fish and by-products were categorized under “both”. (B) By-products category is further classified according to their source (fishery, aquaculture, or unknown).

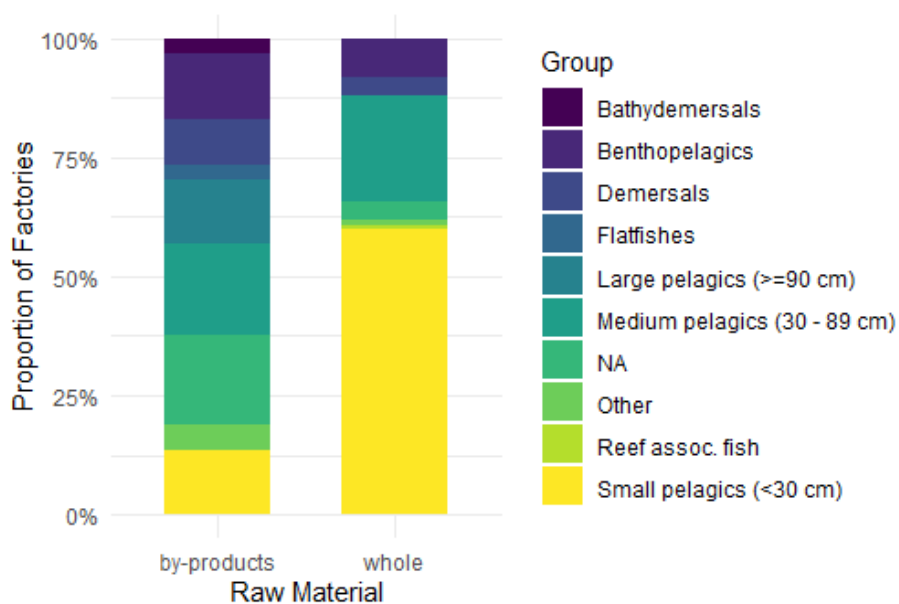


Figure 2-4 Proportion of different species' functional groups used as whole fish or by-products.

Global FMFO production

Production data for the 63 countries included in this study (Figure 2-5) was used to calculate the ratio of fishmeal to fish oil production for each country (Table 2-2). This ratio is variable, ranging among the top 20 producers between 17.8 and 1.1 (Table 2-2, Figure 2-6).

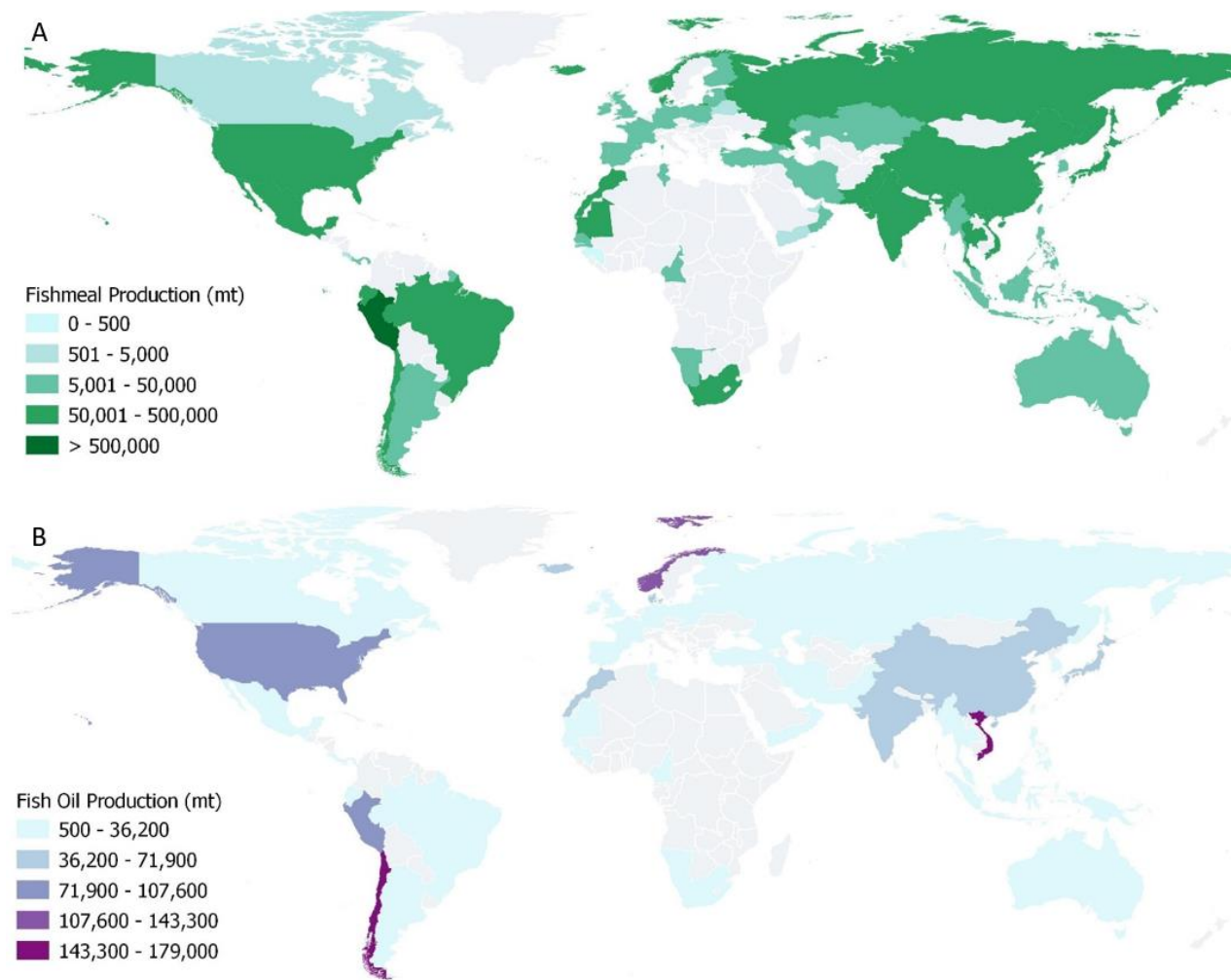


Figure 2-5 Global fishmeal (A) and fish oil (B) production. Production for each producing country is in metric tonnes (t). Darker colors correspond to higher levels of production. Data source: IFFO.

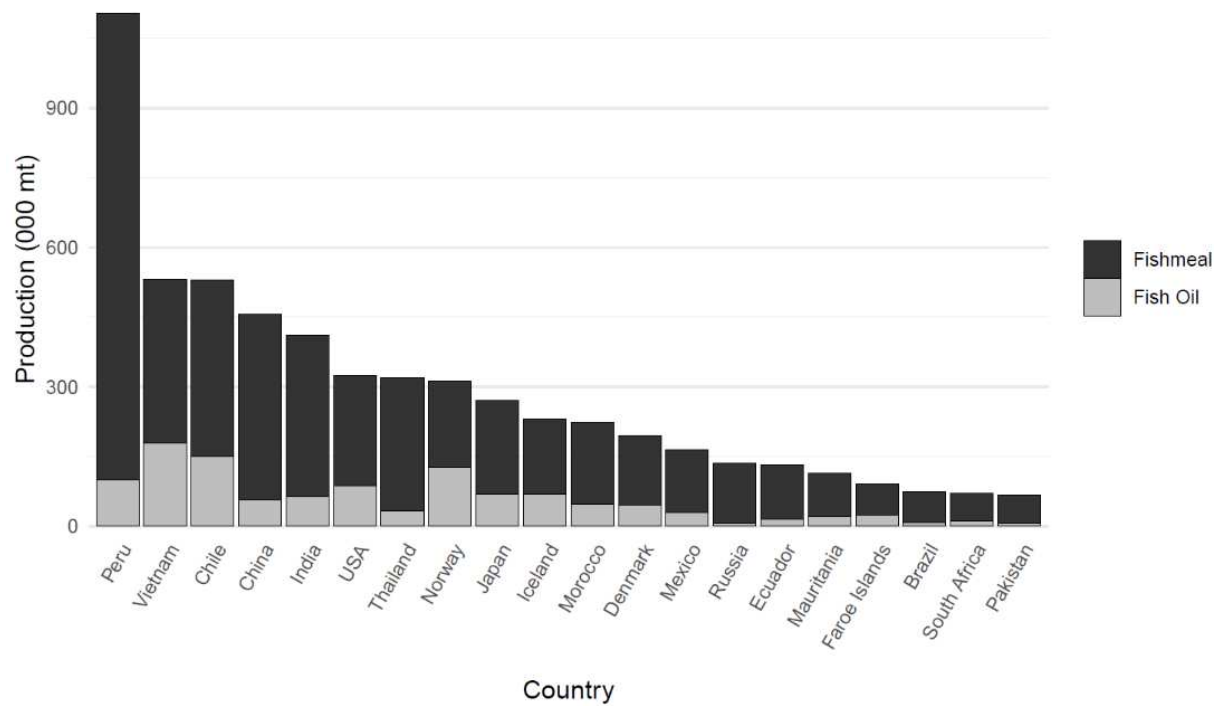


Figure 2-6 FMFO production for the top 20 producing countries in 2022. Data source: IFFO.

FMFO factories and fed aquaculture production

Lastly, we compared the FMFO factory locations to the fed aquaculture production values for each country provided by Clawson et al. (2022) (Figure 2-7). While Clawson et al. (2022) found that China had the highest levels of aquaculture production, followed by Norway and Indonesia, our results show these countries ranked 4th, 8th, and 23rd, respectively, in FMFO production.

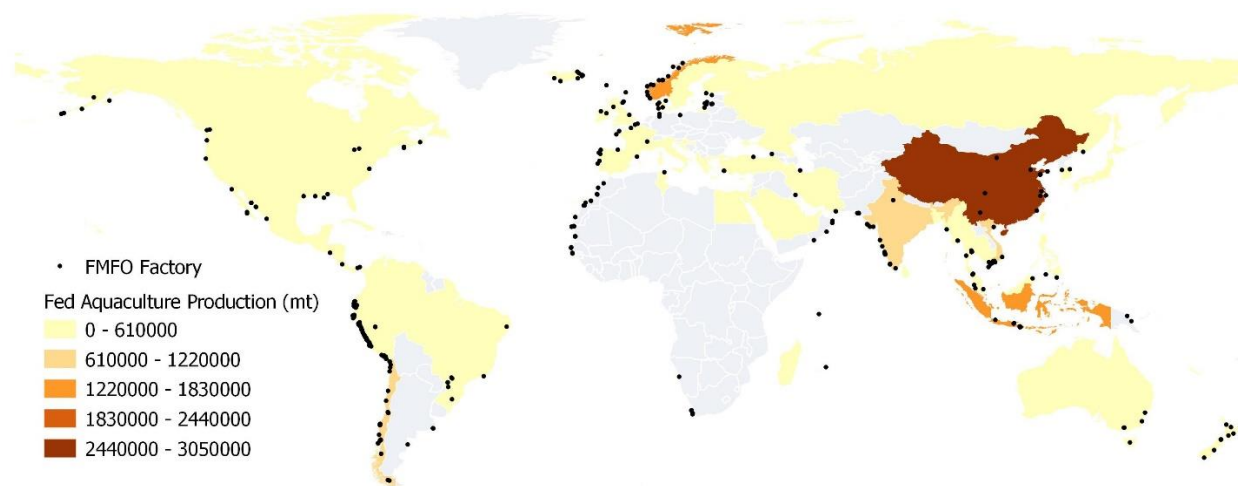


Figure 2-7 Global distribution of FMFO factory locations and aquaculture production. Factory locations are indicated by black dots. Country polygons are shaded to represent fed aquaculture production (t) (data source: Clawson et al., 2022). Darker shades indicate higher production levels. No data was available for countries shaded in grey.

Discussion

Key findings

Through the collection of the data reported in this paper, we generated a map detailing known FMFO factory locations for 63 countries globally. We also gathered information on the raw materials used as inputs, i.e., whole fish or by-products, by these factories for FMFO production. Our database and findings provide a valuable foundation to understand the industry's spatial distribution, some of its key processes, and to identify data gaps. Our results can be utilized in further studies on the trade of marine ingredients and to map the environmental, social, and economic impacts of FMFO factories, with a view to inform the implementation of effective policies in support of responsible FMFO production and use.

Notably, we found that most factories are using fishery and/or aquaculture by-products as raw material for the production of FMFO rather than whole fish. However, as mentioned previously when considering production quantity, a large proportion of FMFO still originates from whole

fish. This is an important consideration for policy-makers trying to better manage the FMFO industry. Regulations should encourage and facilitate the conversion of by-products into FMFO as an effective waste management strategy (FAO, 2024; Rodriguez et al., 2019; Šimat et al., 2019), and consider limiting the use of whole fish reduction to address food and nutrition security concerns as well as fisheries sustainability concerns (Sumaila et al., 2022; Willer et al., 2022).

Our findings also show that the number of FMFO factories in a given country is not an indicator of FMFO production. Factories vary significantly in their production capacities based on the technologies they employ. For instance, European countries, including Norway, Denmark, and Ireland, have few factories but these achieve high production levels. Although FM and FO are co-products, we found high variability across country-level FM : FO ratios. This variability may stem from several factors. It could be the result of differences in the costs and equipment used for producing FO in a given country. It is likely also dependent on the lipid content of raw materials utilized, with some species being higher in oil content than others. Some have also posited that environmental conditions, notably temperature may influence fatty acid content, leading to differences in the yield and quality of oil extracted (Sushchik et al., 2018). Recent work on freshwater fish shows that phylogenetic factors strongly influence their fatty acid composition and omega-3 content, and that the response of EPA and DHA content in fish to temperature variations may be species-specific (Sushchik et al., 2018). The refining processes used to produce fish oil can further influence the amount of oil that is extracted from fish as well as its quality (Ido and Kaneta, 2020).

Study limitations

Our dataset is limited to information that was publicly available online and we are aware that several major producing countries, e.g., China, are not well represented. Reasons for these data gaps include the language used in web-based searches, a lack of national reporting, and the limited online presence of FMFO producing companies. The data search was conducted in English but 46 of the countries included in this study do not have English as an official language. Also, only three countries had a published list of FMFO producers/factories. Most of our data collection efforts relied on materials produced by organizations like IFFO and MarinTrust, membership to which requires significant fees and proof of capacity for membership.

In addition, this study focused on FMFO producers/factories rather than aquatic feed companies. This is an important distinction because aquaculture species are typically not fed FMFO directly. Rather, FMFO are two key ingredients included in compound aquatic feeds formulated by feed companies (Velasco-Escudero and Montoya-Ospina, 2022). Feed producers are an important link between the FMFO producers and aquaculture farms, but were not included in this study.

Next Steps

Collecting this data was both time and resource intensive. Given the dynamic nature of the sector, it is important to regularly update this database to maintain its relevance and accuracy. Better data availability is crucial for understanding the footprint of the FMFO industry and assessing its impacts at local, regional, and global scales. We therefore urge all major FMFO producing countries to officially report information on FMFO production companies and the locations of their factories. This will enhance transparency and facilitate better industry oversight. Mauritania is a role model in this regard as the Institut Mauritanien de Recherches Océanographiques et des Pêches (IMROP) publishes a list of approved FMFO production sites in

their annual report (IMROP, 2023). We also urge FMFO producers to report the types of raw material being used (to the species level), factory production capacity, and annual production data.

This information is critical to improve transparency in the sector. With better information regarding the FMFO industry, we can also better understand industry impacts and inform the development of policies to promote more sustainable, responsible, and equitable practices across the supply chain. Policy-makers must consider how factories and the sourcing of fish to support their operations affect community stakeholders, such as local fishers, processors, and consumers as well as the surrounding environment and management of fisheries. This is especially crucial in areas with high factory density, like coastal towns in Peru.

Future research could build on this data by comparing areas where FMFO factories are performing better or worse environmentally, socially, and/or economically. Additionally, more research is needed on the waste and emissions created by these factories and ways to reduce their environmental impacts (see Tung et al. (2023) for an example).

FMFO are limited resources and though the use of novel feed ingredients is on the rise (Cottrell et al., 2020), they are unlikely to make a significant contribution to the industry for years to come. Therefore, it is crucial to support the environmentally sustainable and socially responsible management of the FMFO industry as it stands. Despite concerns regarding the use of whole fish for FMFO production, it remains an effective waste management strategy for fish processing activities. Policy should be better designed to incentivize by-product rendering for circular food production systems.

3. Projected Impacts of Climate Change on the Fishmeal and Fish Oil

Industry

Introduction

Fishmeal and fish oil (FMFO) are essential components of aquatic feeds. FMFO are typically still produced from whole, wild-caught fish, but can also be obtained from the by-products (e.g., fish heads, tails, and offal) of fish processing (e.g., canning) and aquaculture operations. The use of by-products for FMFO production has been increasing and currently accounts for 34% and 53% of raw materials, respectively (FAO, 2024), contributing to a more circular aquatic food system. Nonetheless, in 2022, approximately 17 million tonnes of global marine catches were used for FMFO production, representing 22% of marine fisheries (FAO, 2024).

The inclusion of FMFO as aquafeed is highly controversial. This controversy stems from the fact that a significant proportion of FMFO is produced by reducing whole, wild fish into flour and oil, that could otherwise be used for affordable human consumption. Given that over 40% of the global population cannot afford a healthy diet (FAO, 2024), informed decisions about our aquatic food systems are essential.

Small (<30cm) pelagic fishes contribute largely to FMFO, followed by medium (30-89 cm) pelagic fishes (Figure 2-3). They are also critical to global food security and livelihoods. These two groups are distinguished by their adult size, but their distinction is most relevant with respect to their role within food webs (Fréon et al., 2005). Small pelagics, which include forage fishes, like sardine and anchovy, consume phytoplankton and small zooplankton, serving as an important link between lower and higher trophic levels within food webs (Cury et al., 2000).

Forage fisheries contribute an estimated USD16.9 billion annually to global fisheries when accounting for both their catch value and the value of fisheries they support (Pikitch et al., 2014). However, this estimate does not fully account for their contributions to food security and nutrition in low-income populations in emerging economies (Bavinck et al., 2023). Medium pelagics, like horse mackerels and coastal tunas, occupy similar niches to small pelagics as juveniles, but feed on larger prey as adults (Fréon et al., 2005).

Small pelagic fishes are most abundant in eastern boundary upwelling regions of the Pacific and Atlantic Oceans (Brodeur et al., 2019), areas where fisheries targeting these species groups are most common and FMFO factories are at their highest density (Figure 2-2). Small pelagic fishes are highly sensitive to environmental conditions, such as El Niño events, with their populations often described as both variable and unstable (Fréon et al., 2005; Lindegren et al., 2013). In 2023, El Niño caused large changes in ocean conditions in the Eastern Pacific and a 50% reduction in industrial landings of Peruvian anchoveta – the largest fishery in the world, by weight, and almost exclusively used for FMFO (FAO, 2024). Such declines severely impacted the global FMFO industry and dependent aquaculture production (Mutter, 2023).

Climate change is driving ocean warming and other changes in environmental conditions, leading to shifts in fish distributions and challenging traditional fisheries management practices (Blanchard and Novaglio, 2024; Cheung, 2018; Pinsky and Fogarty, 2012; Sumaila et al., 2020). Environmental variables, such as temperature, influence fish physiology and in turn, affect movement patterns and population dynamics (Little et al., 2020; Sarre et al., 2024). Rising ocean temperatures associated with climate change have been shown to more negatively impact heavily exploited fish populations (Free et al., 2019). Key challenges to current management include

reliance on steady-state fisheries and lack of adaptation to environmental changes, such as higher temperatures (Pershing et al., 2015) and associated spatial shift in stocks (Gaines et al., 2018).

Climate modeling tools are useful for projecting the impacts of climate change on fish species' abundance and distribution. One example, the Dynamic Bioclimatic Envelope Model (DBEM) (Cheung et al., 2011) projects species' habitat suitability and simulates spatial population dynamics of fish stocks in response to changes in oceanic biogeochemical properties (e.g., temperature, net primary production, and oxygen levels) (Cheung et al., 2016a; Clarke et al., 2021). The DBEM has been used extensively to model changes in species abundance, distribution and projected effect on fish catches for species globally as well as more regionally under different climate scenarios (Cheung et al., 2016b, 2010; FAO, 2018; Lam et al., 2012; Palacios-Abrantes et al., 2022).

In this study, we employ the DBEM to investigate the impact of climate change on the main species caught to produce FMFO. We focus on species used as whole fish, rather than by-products, and use model outputs to explore the potential effect of climate change on the FMFO industry in different regions of the world.

Methods

Global FMFO Industry

In the previous chapter, we located 506 FMFO factories across 63 countries. These countries were selected based on their production of at least 500 t of fish oil in 2022, as reported by The Marine Ingredients Organisation (IFFO), highlighting their significance in the global production and trade of FMFO. In the process of locating factories, we gathered raw material data from

disclosures made by factory owners/companies and certifying agencies. This data was included in our new database and will be made available online, with information detailed to the lowest taxonomic level.

It is important to note that species data used in this study as key to FMFO operations was sourced from the company level, rather than derived from national databases, such as those provided by countries to the FAO. This approach not only provides detailed local information but can also help identify discrepancies in national reporting mechanisms.

Species selection

Raw material data included information on the species used and whether factories sourced it as whole fish or fish by-products. We extracted species listed as “whole” (n=58) from the factory database. Factories (n=9) using invertebrate species (e.g., krill, shrimps, and *Calanus spp.*) as raw material, were excluded from this study. Only species classified to the lowest taxonomic level (i.e., genus and species) were included in the initial species list (n=51). However, due to the unavailability of DBEM abundance simulations for some species, the final analysis included 32 species (Table 3-1).

Our approach differs from previous studies, such as Oyinlola et al. (2022) who used the DBEM to project future changes in FMFO production and the resulting impact on aquaculture production and included a broader range of species and regions. By compiling our species list from raw material data reported by the FMFO industry, we provide a more targeted analysis of climate change impacts on FMFO production. Their study included 114 species in 174 EEZs and

was based on reduction fisheries data included in Cashion et al. (2017). Only 11 species on our list are found in Oyinlola et al. (2022).

Table 3-1 Fish species (n=51) that are reported by factories as raw materials for FMFO production. Species in grey were not available in the DBEM species database, so were excluded from analysis (n=19). Species with an asterisk (*) are included in Oyinlola et al. (2022).

Species (common)	Functional Group	Factory Countries	Relevant Continents
<i>Alutera monoceros</i> (Unicorn leatherjacket filefish)	Medium reef assoc. fish (30-89 cm)	India	Asia
<i>Ammodytes marinus</i> (Lesser sand-eel)	Small benthopelagics (<30 cm)	Denmark	Europe
<i>Anchoa nasus</i> (Longnose anchovy)	Small pelagics (<30 cm)	Ecuador	South America
<i>Atule mate</i> (Yellowtail scad)	Small pelagics (<30 cm)	Vietnam	Asia
<i>Auxis brachydorax</i> (Frigate tuna)	Medium pelagics (30-89 cm)	Ecuador	South America
<i>Brevoortia patronus</i> * (Gulf menhaden)	Medium pelagics (30-89 cm)	United States of America	North America
<i>Caesio erythrogaster</i> (Redbelly yellowtail fusilier)	Medium reef assoc. fish (30-89 cm)	India	Asia
<i>Capros aper</i> * (Boarfish)	Small demersals (<30 cm)	Denmark, United Kingdom	Europe
<i>Cetengraulis mysticetus</i> * (Pacific anchoveta)	Small pelagics (<30 cm)	Ecuador, Mexico, Morocco, Panama, Papua New Guinea	South America, Africa, Asia
<i>Clupea benticki</i> * (Araucanian herring)	Small pelagics (<30 cm)	Chile	South America
<i>Clupea harengus</i> * (Atlantic herring)	Medium pelagics (30-89 cm)	Denmark, Estonia, Finland, France	Europe
<i>Decapterus macrosoma</i> (Shortfin scad)	Medium pelagics (30-89 cm)	Ecuador	South America
<i>Engraulis encrasicolus</i> (European anchovy)	Small pelagics (<30 cm)	Georgia, Germany, Morocco, South Africa, Turkey, UAE	Europe, Africa, Asia
<i>Engraulis mordax</i> * (Californian anchovy)	Small pelagics (<30 cm)	Mexico, Morocco	North America, Africa
<i>Engraulis ringens</i> * (Peruvian anchoveta)	Small pelagics (<30 cm)	Chile, France, Peru	South America, Europe
<i>Ethmalosa fimbriata</i> * (Bonga shad)	Medium pelagics (30-89 cm)	Gambia	Africa
<i>Etrumeus sadina</i> (Red-eye round herring)	Small pelagics (<30 cm)	Mexico, Morocco	North America, Africa
<i>Etrumeus whiteheadi</i> (Whitehead's round herring)	Small pelagics (<30 cm)	Ecuador, Mexico, South Africa	South America, North America, Africa
<i>Eubleekeria splendens</i> (Splendid ponyfish)	Small demersals (<30 cm)	India	Asia
<i>Lutjanus argentimaculatus</i>	Large reef assoc. fish (>=90 cm)	India	Asia

Species (common)	Functional Group	Factory Countries	Relevant Continents
(Mangrove red snapper)			
<i>Maemulpsis axillaris</i> (Roncador)	Medium demersals (30-89 cm)	Ecuador	South America
<i>Mallotus villosus</i> * (Capelin)	Small pelagics (<30 cm)	Norway	Europe
<i>Merlangius merlangus</i> * (Whiting)	Medium benthopelagics (30-89 cm)	United States of America	North America
<i>Micromesistius poutassou</i> * (Blue whiting)	Medium benthopelagics (30-89 cm)	Iceland, Ireland	Europe
<i>Mulloidichthys martinicus</i> (Yellow goatfish)	Medium reef assoc. fish (30-89 cm)	India	Asia
<i>Opisthonema libertate</i> (Pacific thread herring)	Small pelagics (<30 cm)	Mexico	North America
<i>Pentaprion longimanus</i> (Longfin mojarra)	Small demersals (<30 cm)	India	Asia
<i>Peprilus medius</i> (Pacific harvestfish)	Medium benthopelagics (30-89 cm)	Ecuador	South America
<i>Pollachius virens</i> (Saithe)	Large demersals (≥ 90 cm)	France	Europe
<i>Priacanthus tayenus</i> (Purple-spotted bigeye)	Medium reef assoc. fish (30-89 cm)	India	Asia
<i>Pterocaesio chrysozona</i> (Goldband fusilier)	Small reef assoc. fish (<30 cm)	India	Asia
<i>Rastrelliger kanagurta</i> (Indian mackerel)	Medium pelagics (30-89 cm)	India	Asia
<i>Sardina pilchardus</i> (European pilchard)	Small pelagics (<30 cm)	France, Ireland, Mauritania, Morocco, Oman, United Kingdom	Europe, Africa, Asia
<i>Sardinella aurita</i> (Round sardinella)	Small pelagics (<30 cm)	Gambia, Morocco	Africa
<i>Sardinella fimbriata</i> (Fringescale sardinella)	Small pelagics (<30 cm)	Indonesia, India	Asia
<i>Sardinella longiceps</i> (Indian oil sardine)	Small pelagics (<30 cm)	Indonesia, India	Asia
<i>Sardinella maderensis</i> (Madeiran sardinella)	Medium pelagics (30-89 cm)	Gambia, Mauritania	Africa
<i>Sardinops sagax</i> (South American pilchard)	Medium pelagics (30-89 cm)	Indonesia, Mexico, Morocco	Asia, North America, Africa
<i>Saurida tumbil</i> (Greater lizardfish)	Medium reef assoc. fish (30-89 cm)	Vietnam	Asia
<i>Saurida undosquamis</i> (Brushtooth lizardfish)	Medium reef assoc. fish (30-89 cm)	India	Asia
<i>Scomber japonicus</i> (Chub mackerel)	Medium pelagics (30-89 cm)	Ecuador, Mexico, Morocco	South America, North America, Africa
<i>Scomber scombrus</i> (Atlantic mackerel)	Medium pelagics (30-89 cm)	Australia, India, United Kingdom	Oceania, Asia, Europe
<i>Secutor insidiator</i> (Pugnose ponyfish)	Small demersals (<30 cm)	India	Asia
<i>Selar crumenophthalmus</i> (Bigeye scad)	Medium pelagics (30-89 cm)	Vietnam	Asia

Species (common)	Functional Group	Factory Countries	Relevant Continents
<i>Sprattus sprattus</i> (European sprat)	Small pelagics (<30 cm)	Denmark, Estonia, Finland, France	Europe
<i>Trachinocephalus myops</i> (Snakefish)	Small reef assoc. fish (<30 cm)	Vietnam	Asia
<i>Trachurus murphyi</i> (Chilean jack mackerel)	Medium pelagics (30-89 cm)	Chile, Ecuador	South America
<i>Trachurus symmetricus</i> (Pacific jack mackerel)	Medium pelagics (30-89 cm)	Mexico	North America
<i>Trachurus trachurus</i> (Atlantic horse mackerel)	Medium pelagics (30-89 cm)	New Zealand	Oceania
<i>Trichiurus lepturus</i> (Largehead hairtail)	Medium benthopelagics (30-89 cm)	Ecuador	South America
<i>Trisopterus esmarkii</i> (Norway pout)	Medium benthopelagics (30-89 cm)	Denmark, Norway	Europe
<i>Upeneus sulphureus</i> (Sulphur goatfish)	Small demersals (<30 cm)	Vietnam	Asia

Modelling climate change impacts on FMFO species

We assessed impacts on fisheries by evaluating changes in maximum catch potential (MCP), obtained using the Dynamic Bioclimate Envelope Model (DBEM) (Cheung et al., 2011). MCP has been used in previous studies to illustrate potential changes to fisheries due to large-scale warming (Cheung et al., 2016b). For further details about the structure of the DBEM see (Cheung et al., 2024, 2021, 2016b, 2011). We provide a brief summary here.

The DBEM has a spatial grid of 0.5° of latitude x 0.5° of longitude and simulates annual species abundance and catches. The model uses outputs from coupled atmospheric-ocean biogeochemical models which include variables such as, temperature, oxygen, salinity, surface advection, net primary productivity (NPP), bathymetry, and habitat type. Outputs are used to determine habitat suitability for each species in each cell in the spatial grid. The model simulates spatial population dynamics of fish stocks based on logistic population growth, fishing mortality, and the movement of adults and larvae based on advection-diffusion-reaction equations. Biomass is derived from abundance using the average individual mass in each cell. Changes in growth due

to changes in temperature and oxygen levels are modeled assuming growth follows a von Bertalanffy function. MCP is a proxy of maximum sustainable yield (MSY) and is estimated in the DBEM by setting $F = F_{\text{msy}}$.

We projected changes in abundance and distribution and resulting changes in MCP for thirty-two FMFO species between 1950 and 2100 under two climate change scenarios: the strong-mitigation Shared Socioeconomic Pathways (SSP)1-2.6 and the high-emissions SSP5-8.5 scenario. SSP are scenarios used to model the potential impacts of climate change based on varying levels of societal development and environmental policies (Riahi et al., 2017). The SSP are combined with the Representative Concentration Pathways (RCP) that describe different levels of greenhouse gas emissions and other radiative forcings that might occur in the future (Burgess et al., 2023).

The DBEM was driven by simulated ocean conditions from Earth System Models (ESMs), simulating interactions between the atmosphere, oceans, land, and ice to predict climate behavior - from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). CMIP6 provides a standardized set of climate simulations across global centers to improve our understanding of future climate scenarios. Projections of fish species abundance were taken as the average (mean) from DBEM simulations forced by the Geophysical Fluid Dynamic Laboratory (GFDL-ESM4.1) (Dunne et al., 2020) and the Institute Pierre Simon Laplace (IPSLCM6A-LR) (Boucher et al., 2020) ESMs. GFDL-ESM4.1 tends to produce more conservative warming estimates, while IPSLCM6A-LR generally projects stronger warming and more pronounced climate feedbacks.

For analyses conducted at a country scale, MCP was aggregated by summing all DBEM grid cells contained within a country's EEZ boundary for a given species, defined using the *Sea*

Around Us spatial division (updated 1 July 2015; <http://www.seaaroundus.org>). The percent change in species abundance from a historical period (1950-1980) was found by:

$$\% \text{ change in Maximum Catch Potential (MCP)} = \frac{(MCP_{year} - \overline{MCP}_{1950-1980})}{\overline{MCP}_{1950-1980}} * 100$$

Where MCP_{year} is the MCP for a given year and $\overline{MCP}_{1950-1980}$ is the mean MCP between the baseline years 1950 – 1980. A baseline of 30 years was selected to smoothen variations due to natural internal variability in the system (e.g., El Niño Southern Oscillation (ENSO) events). The years 1950-1980 were selected because this time period is before industrial fishing started to cause a strong signal in catch data.

Data analysis and visualization

All data analyses and visualizations were performed in R studio version 4.3.1.

Results

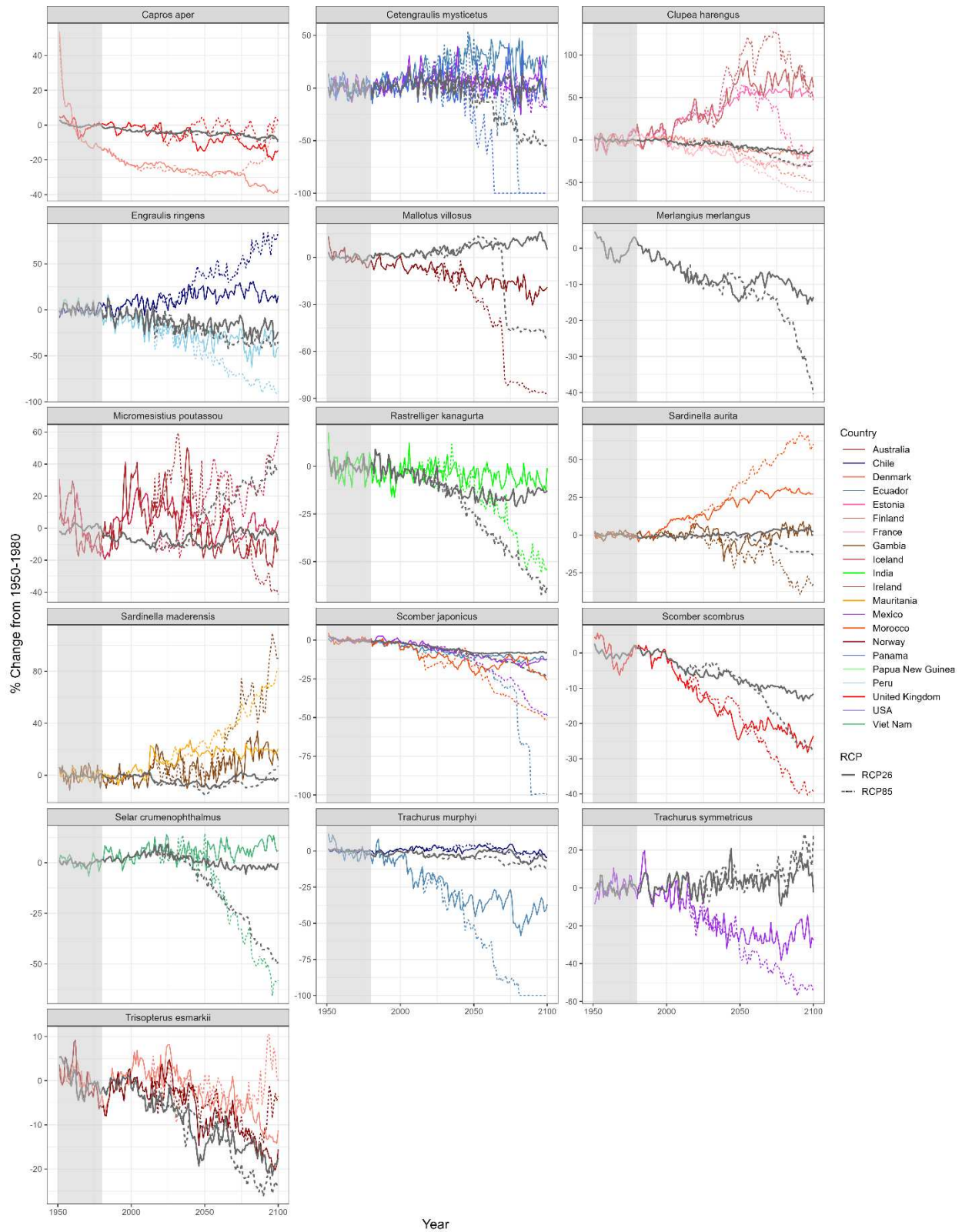
Changes in maximum catch potential (MCP) by species and EEZ

When the change in MCP is plotted for each species, we find high levels of variability between EEZs (Figure 3-1). Some FMFO-producing countries may gain in MCP by the end of the century, while others may experience great losses. For example, the Peruvian anchovy (*Engraulis ringens*), the main source of FMFO along the Pacific coast of South America, is projected to increase in Chile under both emissions scenarios, but decline in Peru. European pilchard (*Sardina pilchardus*), a key raw material for FMFO factories in six countries, shows declines in MCP in all six countries, but projected decreases are most severe for Morocco and Mauritania by the end of the 21st century. The Gambia, a country with a relatively young FMFO

industry (est. in 2017), could see declines in the round sardinella (*Sardinella aurita*) by as much as approximately 30%, possibly due to a northward shift in the population towards Morocco. Overall, most species showed varying degrees of change in MCP by EEZ, that did not always match the average change in MCP calculated across all EEZs.

Changes in MCP by continent

When the change in MCP for FMFO species is summarized by continent, we find that Africa, Asia, Europe, and South America are projected to experience declines ranging from 0.5% to 15% by mid-century under both emissions scenarios (Figure 3-2.A). These declines are expected to be more pronounced for Africa, Europe, and South America under RCP 2.6. In contrast, North America is projected to see an increase in MCP, ranging from 7% (RCP 2.6) to 11% (RCP 8.5). However, by the end of the century, results under RCP 8.5 show declines for all continents, ranging from 27% to 55%, substantially exceeding declines projected under RCP 2.6 (Figure 3-2.B).



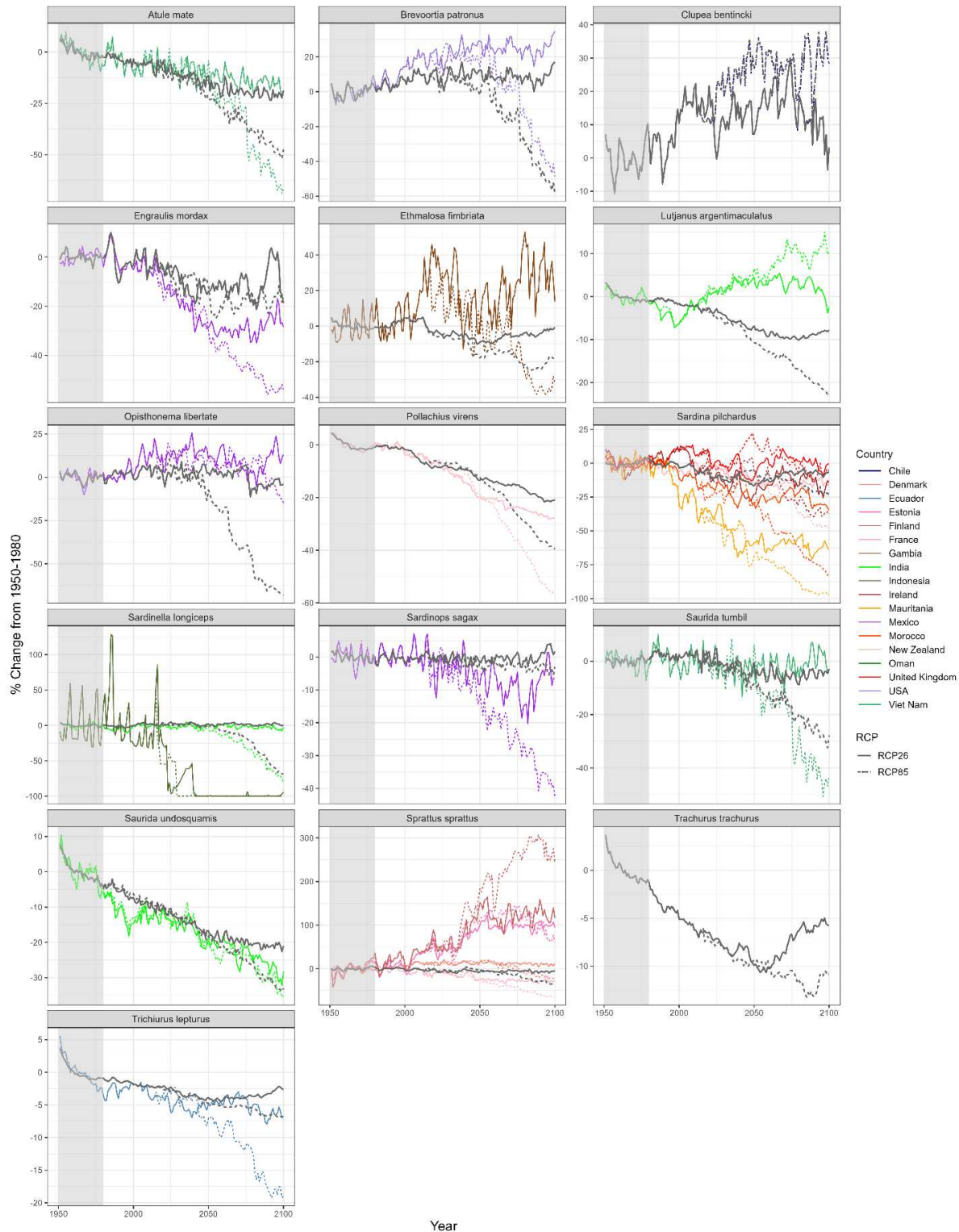


Figure 3-1 Projected percent change in maximum catch potential (MCP) for each species (n=32) under two different emissions scenarios (RCP 2.6 and RCP 8.5) between 1950 and 2100. Colored lines represent projections for a specific EEZ, whereas grey lines represent change in MCP across all EEZs for the species. EEZs that belong to the same continent are assigned different shades of the same color (e.g., African EEZs are all shades of orange). Solid lines represent RCP 2.6 and dotted lines RCP 8.5. The baseline (1950-1980) is shaded in grey.

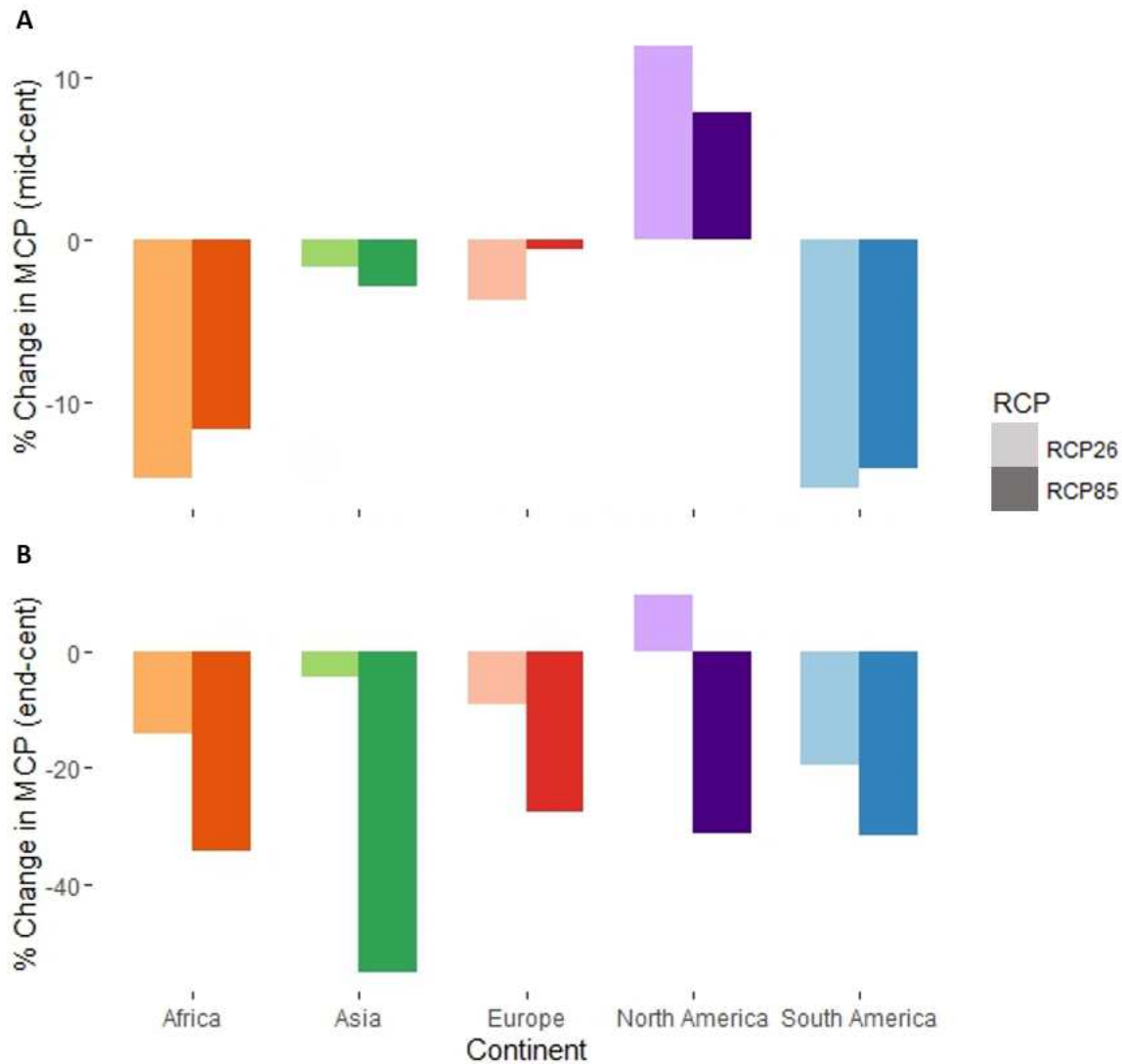


Figure 3-2 Summary of changes in MCP, by continent, of FMFO species for two emissions scenarios, low (RCP 2.6) and high (RCP 8.5). Percent change in MCP is calculated using the average MCP from the baseline (1951-1980) and projections for A) mid-century (2030-2050) or B) end of century (2080-2100). Lighter bars correspond to RCP 2.6 and darker bars to RCP 8.5. The continent color also corresponds to the EEZs in Figure 3-1 (e.g., lines for African EEZs are all shades of orange).

Discussion

In this study, we aimed to determine the impact that climate change could have on the species used for FMFO production by comparing projected MCP by mid-century and end of century. Our results suggest that the global FMFO industry may face negative impacts from climate change, with far worse outcomes projected under a high-emissions scenario by end of century. However, there is substantial variability amongst species and between EEZs. In particular, individual EEZs often had changes in MCP projections that differed from the overall species' projection across all EEZs, illustrating how neighboring countries, such as Chile and Peru, can have vastly different outcomes for the same fish species.

While this is the first study to focus specifically on fish species used as raw material reported by FMFO producers, our findings align with those of Oyinlola et al. (2022) and carry important implications for the climate-resilience of the FMFO industry and ultimately, the fed aquaculture sector. In just two decades, major declines in FMFO species could occur in South America under both a low and high emissions scenario. This is particularly concerning as Chile and Peru rank first and third in global FMFO production, respectively. For both countries, *Engraulis ringens* (Peruvian anchoveta / anchovy) fuels FMFO production, and although the southern anchovy stock is shared between Peru and Chile, there is currently no joint management of the stock (Chávez et al., 2021). This could become problematic as anchovy stocks decline and/or shift, especially during ENSO events. In 2023, an El Niño year, the first anchovy season in the north-central region had to be cancelled due to major stock declines and cost Peru's fishing industry \$1 billion and forced FMFO factories to temporarily shut down for the first time in thirty years (Evans, 2023). For Peru, though the northern anchovy stock is projected to remain within the

Peruvian EEZ (Palacios-Abrantes et al., 2022), even a small shift in the stock geographically and/or in MCP could result in increased production costs and/or major economic losses for the FMFO industry.

In West Africa, top producing countries, such as Morocco and Mauritania, are projected to experience declines in *Sardinella spp.*, which could have serious implications on food security and nutrition in the region (Corten et al., 2017). For example, *Sardinella aurita*, considered a single stock from Morocco to South Senegal (Jurado-Ruzafa et al., 2020), is projected to decline more sharply in the Gambia than Morocco. Currently, there are no regional management agreements for transboundary small pelagic stocks, which has already caused conflict in the region (Dème et al., 2023; Geall et al., 2023). Fisheries management is further strained by a lack of transparency and limited confidence in authorities to manage stocks (Geall et al., 2023). In the Gambia and Senegal, there have been calls for the reduction or abolishment of the FMFO industry due to continued issues regarding fish access, food security, and factory pollution (Geall et al., 2023). Fish used for direct human consumption must be prioritized over fish used for FMFO and policies need to ensure a better balance between economic opportunities presented by value added products (i.e. FMFO) and the food and nutrition needs of communities.

Study limitations and future studies

The DBEM can be constructed using different ESMs, RCPs, and SSPs, than those included in this study. Here, we used SSP1-2.6 and SSP5-8.5 as these two pathways have been widely used and encompass a range of possible outcomes by focusing on the extreme ends (Burgess et al., 2023). Though not included in this study, these scenarios are increasingly combined with other scenarios, like SSP2-4.5, which represents a more moderate scenario. SSP5-8.5 is a high-

emissions scenario but it is important to consider that this approach does not simply represent “business as usual” and includes assumptions that must be understood (Burgess et al., 2023; Moss et al., 2010). Including projections from two ESMs provides for a broader range of potential climate outcomes, capturing uncertainties and variabilities that might not be evident from a single model (Cheung et al., 2016a). This approach enhances the robustness of projections, ensuring that findings are not overly reliant on the assumptions or biases inherent in one model.

Future studies could build on this information by including data on the quantity of each species that is directed towards FMFO in each producing country, thereby weighting the relative impact of changes in MCP for each species across different EEZs. Climate models which use alternative combinations of ESMs, RCPs, and SSPs may also offer different projections and should be taken into account. This information could be used to inform more climate-resilient policy and decision-making.

4. Conclusion

Summary

According to the FAO, aquaculture production has surpassed fisheries catches in recent years and continues to expand (FAO, 2024). While 27% of this growth comes from non-fed species, growth in the fed aquaculture sector, which requires significant feed inputs, remains strong (FAO, 2024). Although feed manufacturers have reduced the proportion of FMFO included in feeds, driven largely by scarcity and rising costs, the complete replacement of FMFO remains challenging. As of 2022, 22% of global marine wild fisheries catch is still processed into non-food products, such as fishmeal and fish oil (FAO, 2024).

The FMFO industry remains controversial in many regions of the world, and this thesis sought to address misconceptions (for example, all FMFO comes from whole fish) and fill key knowledge gaps about the industry. In Chapter 2, I mapped FMFO factories to identify production hotspots and compared factory density with reported production values. Contrary to the prevailing narrative in the literature, I found that most factories were using fish by-products for FMFO production, contributing to a circular aquatic food system. This insight is important for policy reform, as incentivizing the reincorporation of fish processing waste into value-added products could enhance sustainability. The data collected in Chapter 2 will be published online and made publicly-available.

Building on the data and information collected in Chapter 2, I found that the aggregate maximum catch potential for species caught and reduced into FMFO is projected to undergo substantial declines in South America, Africa, Europe, and Asia by mid-century. By the end of the century, all continents are projected to face major declines, with the most severe losses expected under a

high-emissions scenario. These findings underscore the urgent need for more robust fisheries management measures and policy frameworks to mitigate the impacts of climate change on the industry.

Study limitations and future studies

The data presented in Chapter 2 is constrained to publicly available online sources, published in English, and could benefit from the inclusion of languages such as Spanish, Vietnamese, and/or Chinese, as used by the top four FMFO producing countries speak one of those languages. Most countries included in this study lacked comprehensive national datasets on FMFO factories or companies, making the data collection process both time-intensive and challenging. Despite extensive efforts to uncover and compile relevant information, it is likely that some factories were overlooked and the collated dataset does not present a complete picture. Key challenges included finding the exact locations of factories if addresses were not disclosed on the company website or by another organization, such as MarinTrust. The database produced in Chapter 1 would benefit from routine updates and a deeper investigation into each producing country.

Nevertheless, the identified hotspots for FMFO factories generally correspond with known production data, and this information serves as a valuable foundation for further research into the effects that these factories have on surrounding communities and ecosystems. Future studies could expand on this work by comparing locations where FMFO factories are performing well (environmentally, economically, and/or socially) with areas they are not, which could be in the same country.

In Chapter 3, the species included in the DBEM were based on raw material information sourced from factory or company websites. However, discrepancies exist between the species reported as raw material in this study and those identified as key species for the production of FMFO in previous studies (Cashion et al., 2017; Oyinlola et al., 2022). This could be due to the methods used to reconstruct fisheries catch data used in these studies or the selective reporting by factories as to which species they use most often for production rather than all fish species ever used. If factories were missed or factories did not provide raw material data, those fish species would not have been included in our analysis. Additionally, there are inherent limitations to the DBEM (Cheung et al., 2016a) and large variations in projections for each of the species included. The inclusion of a greater number of ESMs or alternative climate scenarios, like SSP2-4.5, could provide a clearer picture of climate projections for FMFO species. It would also be interesting to consider scenarios that estimate potential losses in revenues (Sumaila et al., 2020).

Future research could address some of these gaps by incorporating species reported directly by factories, along with end use data reported by the FAO or reconstructed by the *Sea Around Us* (see www.seaaroundus.org). Studies could also investigate the climate-risk for each FMFO producing country using production quantities, end use data, and climate models to better understand the potential impacts on the industry.

Concluding remarks

The sustainability of marine resources is increasingly challenged as our oceans are facing mounting pressures, especially from climate change. Ensuring that future generations have access to aquatic foods, and that associated livelihood opportunities, nutrition security, economic

opportunities, cultural identity, and traditional practices are preserved hinges on the sustainable management and use of fisheries resources.

Historically, converting fish into FMFO was an effective way to address fisheries surplus and enhance protein and nutrient levels in animal food systems. However, this surplus no longer exists (Pauly and Zeller, 2016). To safeguard global food security, especially in regions where fisheries are crucial to human nutrition, policies should prioritize the use of wild, whole fish for direct human consumption over their use in aquaculture feeds. At the same time, the reduction of fish by-products and waste into FMFO should be promoted and feed companies should be recognized for the integration of this circular approach into their supply chains. One way to incentivize the use of fish by-products for FMFO production could be via certification schemes, though these have limitations and require robust sustainability standards (Saha, 2024, 2022). Encouraging this practice not only contributes to sustainability but also creates economic opportunities by maximizing the value derived from fish processing waste.

This work in this thesis can contribute to greater sustainability in the FMFO industry, and consequently the aquaculture sector, by providing resource managers and policy makers with crucial information regarding where FMFO factories are, which species they are using for production, and how those species are projected to change due to climate change. Governments must work with the industry sector to develop and reform fisheries policies to better strike a balance between economic opportunity, food and nutrition security, local livelihoods, and fisheries sustainability. There are important opportunities for the FMFO industry to evolve into a more sustainable and climate-resilient sector, and it is imperative that this evolution is supported at all levels - international, national, regional, and local.

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Appendix

Data S1. (separate file)

The dataset containing factory information are openly available in Scholars Portal Dataverse at <https://doi.org/10.5683/SP3/P0GLZF>.

Table S1. Data sources for FMFO factory locations and number of factories recorded for each country.

Country	Data sources	Details	No. of Factories
<i>Argentina</i>	IFFO, MarinTrust		4
<i>Australia</i>	IFFO, MarinTrust, Trade-seafood (https://www.trade-seafood.com/directory/seafood/fishmeal-processors.htm)		5
<i>Belarus</i>	NA	Could not find any information regarding FMFO production in Belarus.	0
<i>Brazil</i>	IFFO, Brazilian Renderers (https://brazilianrenderers.com/members/)	Most FMFO factories/companies were available online in a list of Brazilian Meat Renderers. Companies included on this site were only processing by-products.	8
<i>Cameroon</i>	NA	Could not find any information regarding FMFO production in Cameroon.	0
<i>Canada</i>	Government of Canada Industry report (1993), Canadian seafood business directories, MarinTrust	Difficult to find information for Canada and needed to pull information from numerous sources.	7
<i>Chile</i>	IFFO, MarinTrust	Easy to locate factories based on names included in IFFO and Marin Trust members lists.	33
<i>China</i>	MarinTrust, IFFO article (https://www.iffco.com/visit-shandong-province-stronghold-fishmeal-production-china,%20made-in-china.com%20(https://www.made-in-china.com/companysearch.do?subaction=hunt&style=b&mode=and&code=0&comProvince=nolimit&order=0&isOpenCorrection=1&org=top&keyword=&file=&searchType=1&word=fishmeal),go4worldbusiness.com/members)	According to IFFO, most fishmeal production takes place in Shandong province, in the cities Rongcheng and Qingdao. Found a list of producers on a third-party website. No locations could be verified but they were included because China is a significant producer of FM	22
<i>Costa Rica</i>	broad Google search	Difficult to find information. There is a large Biomar feed plant in CR but they are using rather than producing FMFO for aquatic feed products.	1

Country	Data sources	Details	No. of Factories
<i>Denmark</i>	IFFO, Marine Ingredients Denmark (https://maring.org/), EUMOFA, MarinTrust	Denmark is the largest producer in the EU (40-50%); mainly comprised of sprat, herring, sand eels, blue whiting.	5
<i>Ecuador</i>	IFFO, MarinTrust	Mostly by-products from the tuna fishery being used for FMFO production. According to the article below, there are a lot of illegal FMFO operations in Ecuador (https://news.mongabay.com/2023/06/illegal-fishing-for-fish-meal-widespread-in-ecuador-marine-reserve/).	18
<i>El Salvador</i>	FAO (https://www.fao.org/fishery/en/facp/sl?lang=es), MarinTrust	There is a large tuna canning industry here. FMFO most likely comes from tuna fishery by-products.	1
<i>Estonia</i>	EFFOP, MarinTrust		1
<i>Faroe Islands</i>	EFFOP, IFFO, MarinTrust		1
<i>Finland</i>	EFFOP, MarinTrust		1
<i>France</i>	MarinTrust, EFFOP		6
<i>The Gambia</i>	Personal contacts in The Gambia; Outlaw Ocean Project (https://www.theoutlawocean.com/reporting/the-smell-of-money/)		3
<i>Georgia</i>	Trade-seafood; broad Google search		1
<i>Germany</i>	IFFO, EFFOP, MarinTrust		3
<i>Guinea</i>	NA	Difficult to locate any publicly accessible information for Guinea's FMFO production.	0
<i>Iceland</i>	EFFOP, FIF (http://www.fif.is/)	Iceland has a list of producers publicly available for Icelandic Association of Fishmeal Manufacturers.	10
<i>India</i>	IFFO, Trade-seafood	Oil sardine is the main fish used and there are 35 plants operating in Karnataka, Kerala, and Tamil Nadu (35), though these could not all be located. There is also a lot of by-catch being turned into FMFO in India (36).	23

Country	Data sources	Details	No. of Factories
<i>Indonesia</i>	IFFO, Trade-seafood, MarinTrust		11
<i>Iran</i>	Trade-seafood; broad Google search	FAO Country Profile (https://www.fao.org/fishery/en/facp/irn)- "In fact the only possible local source for additional fishmeal, needed by a growing poultry and aquaculture industry, is fish meal produced from lantern fish. In the 6th Five Year Plan, a 70,000 tonnes catch of this species is indicated for the year 2020."	3
<i>Ireland</i>	EFFOP, MarinTrust		3
<i>Japan</i>	Ido and Kaneta (2020)	Urban fisheries biomass by-products (79.4% in 2018) and sardine fishery used for FMFO production.	3
<i>Kazakhstan</i>	primeminister.kz	Kazakhstan imports fish from Norway, Russia, Iceland, China and the Baltic countries and then annually exports 30 thousand tonnes of fish products worth about \$60 million to 36 countries of the near and far abroad.	1
<i>South Korea</i>	IFFO		2
<i>Latvia</i>	EFFOP, Broad Google search	Difficult to find processing plant addresses provided on websites, so we needed to geocode the addresses.	5
<i>Lithuania</i>	Broad Google search	Most companies that were found during Google searches were suppliers of fishmeal but not producing it themselves. Most fishmeal being imported from Morocco, Mauritania, and Denmark.	1
<i>Malaysia</i>	Polaris Market Research, Broad Google search, MarinTrust		4
<i>Mauritania</i>	(IMROP, 2023)	There was a strong development in the FMFO industry after 2010. Main FMFO factory hubs are in Nouadhibou and Nouakchott.	42
<i>Mauritius</i>	IFFO, MarinTrust		1
<i>Mexico</i>	IFFO, MarinTrust	small pelagics and tuna by products mostly	11
<i>Morocco</i>	IFFO, Marin Trust, Seafood from Morocco, Trade-seafood		15
<i>Myanmar</i>	Broad Google search and Polaris Market Research		5

Country	Data sources	Details	No. of Factories
<i>Namibia</i>	Ministry of Environment and Tourism (https://www.meft.gov.na/files/downloads/179_ResMob-Inventory%2520report2-final.pdf&sa=U&ved2ahUKEwjgqbrGp96FAxV7FzQIHcvFAxEQFnoECAEQAAQ&usg=AOvVaw3Yr60v69xgdrUOARSLA0HI&arm=e)	“The processing of pelagic fish (horse mackerel and their juveniles) has been important part of local economies in Walvis Bay and Luderitz.” Difficult to find individual factories in Namibia.	1
<i>New Zealand</i>	New Zealand Ministry for Primary Industries	List of FMFO producers is online and publicly available in MPI data base.	10
<i>Norway</i>	IFFO, EFFOP, MarinTrust	Easy to get detailed information, find locations, and websites.	17
<i>Oman</i>	IFFO, Trade-seafood		5
<i>Pakistan</i>	Trade-seafood		3
<i>Panama</i>	IFFO, MarinTrust		2
<i>Papua New Guinea</i>	Trade-seafood	Tuna canning operations turning waste into FMFO.	2
<i>Peru</i>	Personal communications	List of FMFO factories with site addresses, raw material information, and production capacity.	125
<i>Philippines</i>	IFFO, MarinTrust, Trade-seafood	Tuna canning operations turning waste into FMFO.	2
<i>Poland</i>	MarinTrust		1
<i>Portugal</i>	Euro pages	Producers listed on Euro pages.	2
<i>Russia</i>	IFFO, Trade-seafood	Difficult to find information in English that was also publicly available.	2
<i>South Africa</i>	IFFO, MarinTrust		5
<i>Samoa</i>	MarinTrust	Difficult to find any factories in American Samoa.	1
<i>Senegal</i>	Greenpeace Africa	Difficult to find list in English and publicly available online.	1
<i>Seychelles</i>	European parliament	Tuna fishery by-products.	1
<i>Slovakia</i>	NA		0

Country	Data sources	Details	No. of Factories
<i>Spain</i>	IFFO, MarinTrust		5
<i>Taiwan</i>	Trade-seafood	Difficult to find list in English and publicly available online.	1
<i>Thailand</i>	MarinTrust	All from tuna fishery by products.	12
<i>Tunisia</i>	IFFO, Broad Google search		2
<i>Turkey</i>	Trade-seafood, turkey-manufacturers (https://www.turkish-manufacturers.com/fishmeal-turkey.html)		4
<i>UAE</i>	Broad Google search		3
<i>United Kingdom</i>	EFFOP, MarinTrust		5
<i>USA</i>	IFFO, MarinTrust		14
<i>Vietnam</i>	IFFO, MarinTrust, Polaris Market Research, Trade-seafood		16
<i>Yemen</i>	Trade-seafood		4