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Assessing the potential economic effects of mesopelagic fisheries as a novel source of fishmeal

Rohan Gowda Thanh Quang[1] | **Melina Kourantidou**[2,3,4] | **Di Jin**[2]

[1]Biology Department, Pomona College, Claremont, California, USA

[2]Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

[3]Department of Sociology, Environmental and Business Economics, University of Southern Denmark, Esbjerg Ø, Denmark

[4]Université de Bretagne Occidentale, AMURE, Plouzané, France

Correspondence

Di Jin, Marine Policy Center, Woods Hole Oceanographic Institution, USA.
Email: djin@whoi.edu

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Abstract

The continuous growth of the aquaculture industry implies increased demand for efficient sources of aquafeed, such as fishmeal. Pelagic fish are a desirable source of fishmeal due to their high nutritional content. Nevertheless, several pelagic stocks that have been exploited extensively for fishmeal production face ecological limits due to commercial exploitation, and the aquaculture industry is now seeking novel, efficient, and sustainable sources of aquafeed. The mesopelagic zone, an ecosystem with many scientific uncertainties, is being considered as a potential source for fishmeal, largely owing to the abundance of mesopelagic fish and their robust nutritional profile. However, both the ecological and economic viability of commercial exploitation of mesopelagic fish are not yet well understood. To understand the conditions that would make such an endeavor economically viable in the context of global fishmeal production systems, we use a bioeconomic model that assesses the economic consequences of including mesopelagic fish as a fishmeal source. Through simulations, we assess the economic implications of this hypothetical mesopelagic

fishery on major pelagic fishmeal production systems. The mesopelagic fishery can be economically profitable for harvesters, and its addition to global fishmeal production reduces fishmeal market price, thus making it more accessible to aquaculture farmers and less profitable for pelagic fishers. While this may reduce fishing pressure on pelagic forage-fish stocks, the implications of commercial exploitation of mesopelagic on key ecosystem services remain a concern.

KEYWORDS
aquaculture, fishmeal, forage fisheries, markets, mesopelagic, profitability

Recommendations for Resource Managers

- The continuous growth of the aquaculture industry implies increased demand for efficient sources of aquafeed, such as fishmeal.
- Several pelagic stocks that have been exploited extensively for fishmeal production face ecological limits due to commercial exploitation, and the aquaculture industry is now seeking novel, efficient, and sustainable sources of aquafeed.
- The mesopelagic zone is being considered as a potential source for fishmeal. However, both the ecological and economic viability of commercial exploitation of mesopelagic fish are not yet well understood.
- We use a bioeconomic model to assess the economic consequences of including mesopelagic fish as a fishmeal source and the economic implications of this hypothetical fishery on major pelagic fishmeal production systems.
- The results show that mesopelagic fishery could be profitable for harvesters, and its addition to global fishmeal production would reduce fishmeal market price, thus making it more accessible to aquaculture farmers and less profitable for pelagic fishers.

1 | INTRODUCTION

The aquaculture industry is the fastest-expanding food sector worldwide, driven by both income and population growth (Bouelet Ntsama et al., 2018; Naylor et al., 2021). Rising income levels have increased consumer food diversification, leading to higher spending on luxury items which include imported seafood. Further, recent decades have shown significant growth in aquatic food production and consumption, including in developing and least-developed countries, demonstrating clear associations with food and nutritional security (FAO, 2022; Garlock et al., 2022). Of the developmental conundrums within aquaculture, identifying aquafeed sources that are nutritious, economically and environmentally sustainable is of primary concern. Currently, aquaculture relies predominantly on forage fish from capture fisheries which are reduced to fishmeal/fish-oil (hereafter, we use "fishmeal" to reference both fishmeal and fish-oil) (Froehlich et al., 2018). However, as capture fisheries supply plateau due to ecological limits, aquaculture production systems are adopting novel feed sources and formulations to reduce their reliance on wild forage fish. Yet, these efforts have yielded mixed results as the feeds' nutritional content—omega-3 fatty acids, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), specifically—needed for healthy fish growth is oftentimes compromised, unless some fishmeal is included in the aquafeed mixture (Geay et al., 2011; Liu et al., 2020, 2021).

Marine living resources from the mesopelagic or "Ocean Twilight Zone," defined as waters from approximately 200 to 1000 m in depth, are being considered for exploitation as a novel source of fishmeal for aquaculture (Alvheim et al., 2020; Grimaldo et al., 2020; Olsen et al., 2020). Their high nutritional content, particularly in terms of long-chain polyunsaturated fatty acids, makes them excellent candidates for fishmeal production (Grimaldo et al., 2020). Although mesopelagic fish biomass estimations vary widely, from 2.4 to over 15 billion metric tons, it is believed to be of scale incomparably larger than any existing commercial fish stock (Anderson et al., 2019; Irigoien et al., 2014). Experimental catch surveys in Norway found glacier lanternfish (*Benthosema glaciale)* and Mueller's pearlside (*Maurolicus muelleri*)—two abundant fish in the mesopelagic—to contain high EPA, DHA, and protein content, along with low levels of substances unsuitable for human consumption (Grimaldo et al., 2020). While the mesopelagic shows promise as a fishmeal source, commercial operations remain unviable due to technological limitations which impede catch and processing efficiency, which ultimately limits profitability (FAO, 1997; Roberts et al., 2020; Sigurdsson et al., 2015; Standal & Grimaldo, 2020; Valinassab et al., 2007). However, continued technological development and research, coupled with industry interest, and opportunities created by fisheries regulation of other species are expected to lift these economic barriers and allow the exploitation of mesopelagic resources to supply the fishmeal industry; such development is desirable in terms of global food and nutrition security (Gatto et al., 2023; Kourantidou & Jin, 2022; Paoletti et al., 2021; Prellezo, 2019).

Despite the abundance of mesopelagic resources, there are concerns that commercial exploitation may undermine important ecosystem services in multiple ways. These concerns pertain to the role of mesopelagic organisms as prey for higher trophic levels (Naito et al., 2013; Smith et al., 2011), and as a key component of the biological carbon pump and therefore carbon sequestration, through the diel vertical migration (Buesseler et al., 2022; Roberts et al., 2020; Saba et al., 2021). In practice, this means that the development of mesopelagic fisheries could possibly endanger conservation of ecologically and/or commercially important large marine mammals and fish (i.e., dolphins, sharks, whales, billfish, rays, and tunas) and disrupt carbon

sequestration irreversibly, thus proving very costly to human wellbeing (Buesseler et al., 2022; Dowd et al., 2022; Hidaka et al., 2001; Johnson, 2012; Mariani et al., 2020; Martin et al., 2021; Roberts et al., 2020; Saba et al., 2021; Smith et al., 2011).

In this paper, we assess the implications of including mesopelagic fish as a new fishmeal source via economic linkages between fishmeal production systems. We run simulations using a bioeconomic model that allows us to understand how pelagic fishmeal production responds to the inclusion of hypothetical, economically viable mesopelagic fisheries. We discuss our results in the context of the global fishmeal sector and the needs of the aquaculture sector, along with the viability and expectations for an emerging mesopelagic fishery and relevant policy implications.

2 | METHODS

The model used in the study is an extension of the modeling framework of Merino et al. (2010) by adding a hypothetical mesopelagic fishery to three major forage-fish fisheries: Humboldt Current, Asia, and Europe. For the population dynamics of each of these fisheries, we use the standard logistic growth model and the Schaefer harvest function (see Appendix Figure A1 for the growth function of the four fisheries, including the mesopelagic):

$$X_i(t+1) = X_i(t) + r_i X_i(t)\left(1 - \frac{X_i(t)}{K_i}\right) - Y_i(t), \tag{1}$$

where index i denotes the four production systems; $X_i(t)$ is the stock in fishery i and year t; r and K are the intrinsic growth rate and carrying capacity, respectively; and Y is the harvest:

$$Y_i(t) = \max[q_i E_i(t) X_i(t), Quota_i(t)], \tag{2}$$

which is given by the Schaefer (1954) harvest function $q_i E_i(t) X_i(t)$, with q as the catchability coefficient and E as the fishing effort, subject to a fishing quota constraint. The quota is set at maximum sustainable yield (MSY):

$$Quota_i(t) = Y_{MSY_i} = \frac{r_i K_i}{4}. \tag{3}$$

The global fishmeal market is modeled through a linear demand function as follows:

$$p(t) = \alpha - \beta Q(t), \tag{4}$$

where p is the fishmeal price, α is the choke price, β is the slope of the demand curve, and Q is the aggregate quantity of fishmeal supplied to the market, which is the sum of supplies from different fishmeal production systems:

$$Q(t) = \sum_{i=1}^{4} Q_i \tag{5}$$

with

$$Q_i(t) = \lambda_i Y_i, \tag{6}$$

where λ is the yield-to-meal transformation ratio.

As fishmeal production systems all supply to a common global market, each system's production is linked to and determined by production from other systems, resulting in an economic equilibrium that determines the market price and quantity to be supplied (Mullon et al., 2009).

The net profit (R) for each fishmeal production system is calculated as

$$R_i(t) = \lambda_i p(t) Y_i(t) - f_i E_i(t) - m_i Y_i(t) - s_i d_i Q_i(t), \tag{7}$$

where f is the unit cost of fishing effort, m is the cost of reducing fish into fishmeal, s is the cost of shipping fishmeal to international markets, and d is the distance to main consumers.

Each fishery adjusts their fishing effort based on expected future profits, which are determined by past economic performance (Merino et al., 2010; Mullon et al., 2009). Specifically, the fishing effort is updated as follows:

$$E_i(t+1) = E_i(t) + j_i\left(\frac{R_i(t)}{v_i}\right), \tag{8}$$

where v is the price of a new fishing unit, and j is a coefficient controlling investment in additional fishing effort.

When all fisheries are managed to maintain their MSYs, the long-term steady-state fishmeal supply quantity and price at the global market are given by the following system of equations:

$$Q_{MSY} = \sum_{i=1}^{4} \lambda_i Y_{MSYi}, \tag{9}$$

$$p_{MSY} = \alpha - \beta Q_{MSY}. \tag{10}$$

We characterize the pelagic fish production systems in three regions: the Humboldt Current (Peru and Chile, harvesting Peruvian anchoveta), Asia (Vietnam, China, and Thailand, harvesting Japanese anchovy), and Europe (Norway and EU, harvesting North Sea sandeel). Together, they comprise close to 70% of global fishmeal production and consumption (IndexMundi, 2023; Merino et al., 2010). Monthly fishmeal prices 2014–2023 can be found in Figure A2 in the appendix. Initial fishmeal production was updated using data from IndexMundi (Table 1), and cost data were adjusted to 2023 dollars using price index (US GDP deflator). Data for the mesopelagic fishery was from Kourantidou and Jin (2022). Bioeconomic parameters for the mesopelagic are largely uncertain, but they are generally known to be less favorable than those for the existing production systems. For the simulation, the mesopelagic fishery has lower catchability as well as higher fishing cost (EUMOFA, 2018; Kourantidou & Jin, 2022; Underwood et al., 2021). In addition, we include the cost of adding new vessels. Table 2 presents the parameters used for model simulations.

Our model treats the whole ocean mesopelagic zone as a single fishery (harvesting Mueller's pearlside or Glacier lanternfish that are the most commonly targeted species and part of sampled families; Fjeld et al., 2023), ecologically and technically separate from the regional pelagic production systems; only an economic linkage is considered. Realistically, fishing in the

TABLE 1 Fishmeal production (10^3 t/year).

	Humboldt		Asia			Europe	
Year	Peru	Chile	Vietnam	China	Thailand	Norway	EU
2014	754	450	423	450	450	200	455
2015	660	450	450	400	480	204	480
2016	972	435	435	436	350	210	466
2017	1000	368	450	400	335	230	420
2018	1068	345	470	364	340	220	435
2019	910	410	460	350	335	230	405
2020	1169	370	450	350	340	230	400
2021	1150	369	530	365	350	220	400
2022	1100	369	440	400	340	230	400
2023	1100	375	500	430	370	230	400
Country mean	988.3	394.1	460.8	394.5	359	220.4	426.1
Regional mean	1382.4		1214.3			646.5	

Source: IndexMundi compilation of US Department of Agriculture data. https://www.indexmundi.com/Agriculture/?commodity=fish-meal&graph=production.

mesopelagic may exert technical (e.g., vessels crowding out ground space from other pelagic fleets) and ecological (e.g., predator–prey and competition relationships) impacts on pelagic production systems in the same region (Ulrich et al., 2002). Further, fisheries operating in the same region are unlikely to target pelagic or mesopelagic fish exclusively; rather, fisheries would exploit both resources, either incorporating seasonal operations or expanding current pelagic fleets to house the increased catch from the mesopelagic (Standal & Grimaldo, 2020). However, these points are beyond the scope of this study.

3 | RESULTS AND DISCUSSION

As discussed in Kourantidou and Jin (2022), a large-scale mesopelagic fishery is potentially viable in terms of economic profitability in the near future under certain price and fishing cost conditions. Figure 1 depicts the mesopelagic fishery in its first 10 years. Increasing fishing effort and harvest will drive down the stock as well as the global fishmeal price. As a result, the initial profit level will not be maintained. In the model, all four fisheries will be under quota management with MSY as constraints (Equations 2 and 3), so that the mesopelagic stock will not collapse in the long run (see Figure A3 in the appendix).

We use “Scenario 1” to denote simulation results without incorporating the mesopelagic fishery, while “Scenario 2” denotes results incorporating the mesopelagic. In both scenarios, changes in total fishmeal production and fishmeal price follow similar trajectories, differing mainly due to the additional quantity of fishmeal provided by the mesopelagic (Figure 2). We emphasize that fishmeal production is a supply function that is conditioned on the linear demand function specified for the baseline simulation

TABLE 2 Baseline parameters for the simulation.

Variable	Description	Unit	Humboldt ($i = 1$)	Asia ($i = 2$)	Europe ($i = 3$)	Mesopelagic ($i = 4$)
$Q_i(0)$	Initial fishmeal production	Mt year^{-1}	1.38	1.21	0.65	0.004
$Y_i(0)$	Initial fish production	Mt year^{-1}	6.00	2.68	2.41	0.02
K_i	Carrying capacity	Mt	49.99	18.95	6.4	100
$X_i(0)$	Initial fish stock	Mt	18.5	9.47	3.2	100
r_i	Intrinsic growth rate	year^{-1}	1	0.5	0.991	0.478
q_i	Catchability coefficient	10^{-6} fishing unit^{-1}	1.5	1.42	1.93	1
$E_i(0)$	Initial fishing effort	Total fishing unit (m^3)	63,206	58,052	42,500	65,000
$Emax_i$	Maximum fishing effort	Total fishing unit (m^3)	200,000	55,000	50,000	200,000
f_i	Fishing costs	\$ fishing unit^{-1}	65	65	103.48	105
v_i	Price of increasing fishing capacity	\$ m^{-3}	2600	2860	5850	6500
m_i	Fishmeal transformation costs	\$ t^{-1}	130	260	294.71	260
s_i	Shipping costs	\$ t^{-1} km^{-1}	0.026	0.026	0.026	0.026
d_i	Distance to main consumer	km	13,000	500	500	600
j_i	Fleet investment coefficient	Dimensionless	0.2	0.2	0.2	0.2
α	Choke fishmeal price	\$ t^{-1}	1700			
β	Slope of demand curve	\$ t^{-2}	60			

Abbreviations: Mt, 10^6 metric tons; t, metric ton.

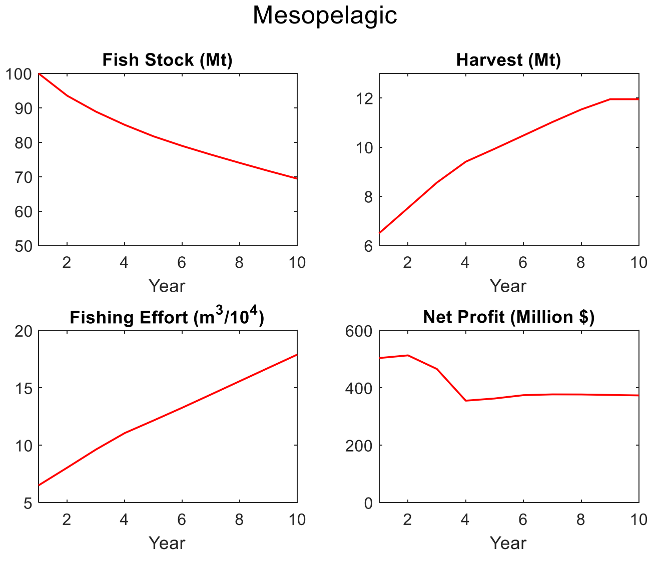

FIGURE 1 Simulation results for the mesopelagic fishery.

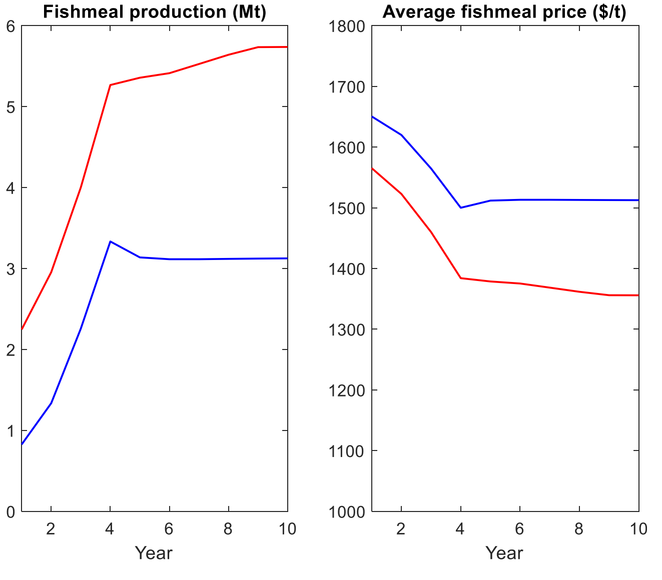

FIGURE 2 Simulation results for the global fishmeal market. (Left) Fishmeal traded in the global market (million metric tons). (Right) Fishmeal market price. The blue line denotes trajectory without the mesopelagic fishery (Scenario 1). The red line denotes trajectory incorporating a mesopelagic fishery (Scenario 2).

(Table 2); as long as fish stocks are above the levels corresponding to MSYs, total production output is able to increase. By Year 10, Scenario 2 yields 5.74 Mt of fishmeal produced, suggesting that global fishmeal supply could meet its projected production of 5.6 Mt by 2031 (OECD & FAO, 2022). Larger fishmeal production drives price down for Scenario 2, making it more accessible for aquaculture farmers to source as aquafeed, facilitating the continued growth of the industry.

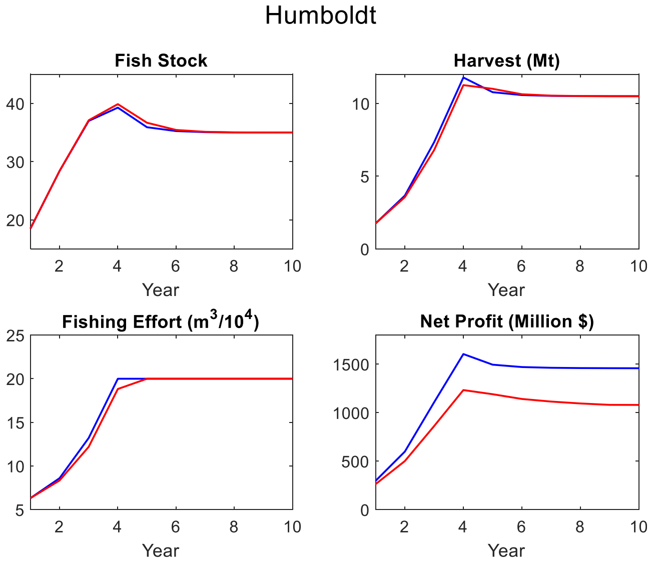

FIGURE 3 Simulation results for the Humboldt Current. The blue line denotes trajectory without the mesopelagic fishery (Scenario 1). The red line denotes trajectory incorporating a mesopelagic fishery (Scenario 2).

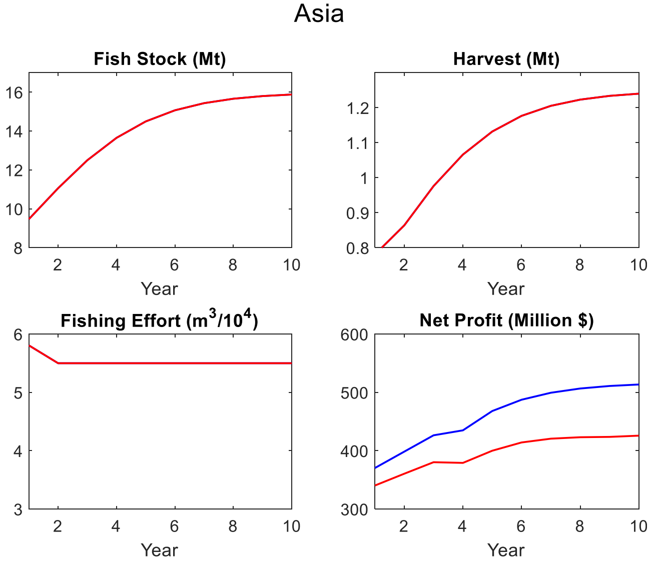

FIGURE 4 Simulation results for Asia. The blue line denotes trajectory without the mesopelagic fishery (Scenario 1). The red line denotes trajectory incorporating a mesopelagic fishery (Scenario 2).

Simulated global fishmeal production in Scenario 2 increases until Year 4, after that annual increase rate becomes lower (Figure 2). The rapid increase in production between Years 1 and 4 is a result of increased fish harvests in all four production systems under quota management (Figures 1 and 3–5). This is most evident when looking at the three existing production systems in Humboldt Current, Asia, and Europe, where harvest and fish stock levels both increase until Year 4, after which

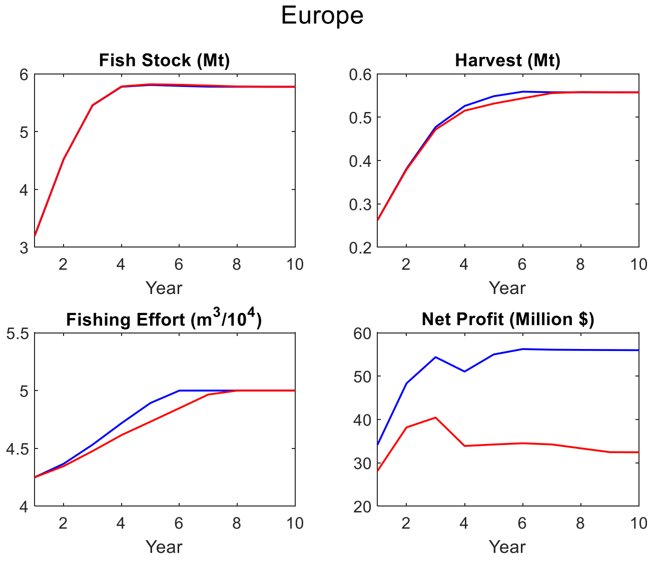

FIGURE 5 Simulation results for Europe. The blue line denotes trajectory without the mesopelagic fishery (Scenario 1). The red line denotes trajectory incorporating a mesopelagic fishery (Scenario 2).

an equilibrium is reached such that harvest level roughly equals stock replenishment, with fishing quota set at MSY (Figures 3 and 5). For Asia, the simulated effort control leads to stock growth and increased harvest (Figure 4). Introducing a mesopelagic fishery has considerable impacts on their net profits (Figures 3–5). This is due to the lowered price for fishmeal, making each of the existing systems less profitable. In contrast, the mesopelagic fishery has a small negative or negligible impact on stock, harvest, and fishing effort for the three pelagic production systems. This is because in the model, different fisheries are linked only through the fishmeal market, and the three exiting forage-fish production systems are affected only by the change in fishmeal price. Fishing efforts and harvests will be mostly the same when positive profits are maintained (Equation 7). Minor variations are due to adjustment in fishing effort with respect to profit (Equation 8). Because of overcapacity, the effort reduction and the associated stock and harvest in Asia follow the same trajectory with or without the mesopelagic fishery.

Overall, the model simulation results suggest that sourcing fishmeal from the global mesopelagic stock may be economically profitable for mesopelagic harvesters. The reduction in fishmeal price also makes it a more economically viable feed source for aquaculture farming. On the other hand, a lower price leads to profit reductions for existing forage-fish production systems. Incorporating the mesopelagic fishery as an additional source of fishmeal presents a significant economic opportunity, but ecological and environmental impacts need to be carefully considered to prevent potential overfishing, local extinction, and subsequent resource depletion.

It is important to note that the potential economic effects of mesopelagic fisheries as a source of fishmeal are sensitive to future demand conditions. Assuming that, in the long-run steady state, all four fisheries are well managed with harvests at their MSY levels. The total fishmeal supply quantity will be 4.37 million metric tons under Scenario 1 and 6.98 million metric tons under Scenario 2. However, the corresponding fishmeal price and, in turn, fisheries' profitability, will be different depending on the demand parameters (Equations 9 and 10). As shown in Table 3, under the baseline parameters ($\alpha = 1700$ and $\beta = 60$), the fishmeal price is \$1438/t (Scenario 1) and \$1281/t (Scenario 2),

TABLE 3 Global fishmeal price at steady state under different demand parameters.

		β		
Scenario	α	**60**	**120**	**180**
1	1700	1438	1175	913
2		1281	862	443
Change (%)		10.90	26.70	51.50
1	2100	1838	1575	1313
2		1681	1262	843
Change (%)		8.50	19.90	35.80
1	2500	2238	1975	1713
2		2081	1662	1243
Change (%)		7.00	15.90	27.40

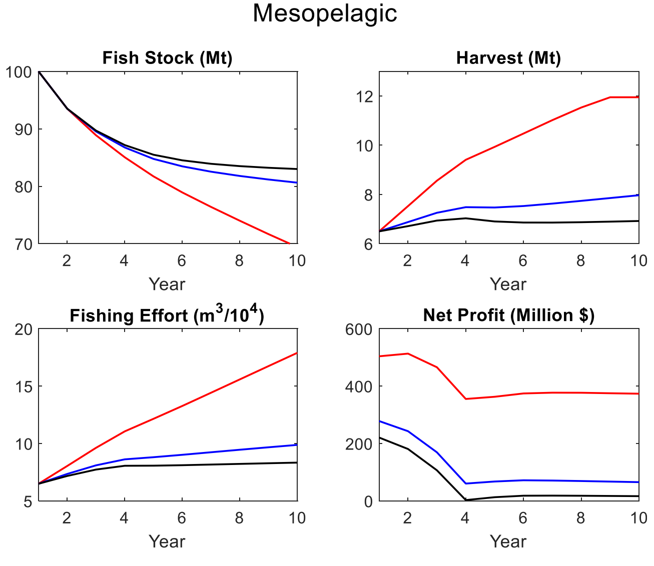

FIGURE 6 Simulation results for the Mesopelagic fishery at three fishmeal transformation costs: \$260/t (cost in Asia, red), \$294.71/t (cost in Europe, blue), and \$303.55/t (3% higher cost than that in Europe, black).

respectively. With growing demand, the fishmeal price will be higher (\$2081/t when $\alpha = 2500$), and all fisheries more profitable. Changes in the demand slope (β) will make the effects of adding the mesopelagic fishery more significant (greater difference between prices under Scenarios 1 and 2).

4 | SENSITIVITY ANALYSIS

We conduct a sensitivity analysis with respect to the most influential parameters which control the economic viability of fishmeal from the mesopelagic fishery and the fishmeal demand function. Figure 6 summarizes the results of model runs at three different fishmeal

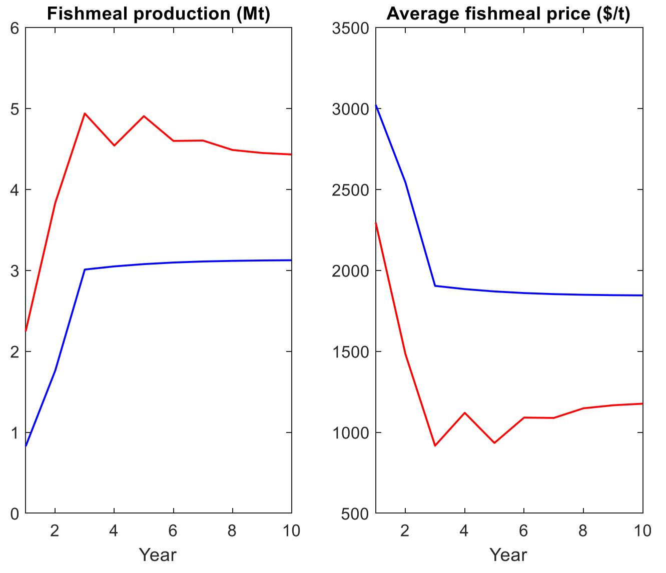

FIGURE 7 Sensitivity analysis: global fishmeal market under a steeper sloped demand curve (compared with the baseline). The blue line denotes trajectory without the mesopelagic fishery (Scenario 1). The red line denotes trajectory incorporating a mesopelagic fishery (Scenario 2).

transformation costs ($260, $294.71, and $303.55/t). The simulation results suggest that if the fishmeal transformation cost for mesopelagic is more than 3% of that for the European production system ($303.55/t), the mesopelagic fishmeal production would not be profitable.

Another concern is that a sharp increase in fishmeal supply could lead to a large reduction in price, affecting fishery profitability. This effect can be simulated by increasing the slope of the demand function (Equation 4). Using the data on fishmeal production quantity and price (in Table 1 and Figure A2), we estimated the demand parameters as $\alpha = 3{,}445$ and $\beta = 512$, which are similar to the parameter values in Mullon et al. (2009). This slope is significantly steeper than that of our baseline demand function ($\alpha = 1{,}700$ and $\beta = 60$), so that the price drop is more profound in response to a surge in fishmeal supply from the mesopelagic. Selected results of simulations using the steeper demand curve are depicted in Figures 7–9. The introduction of a large-scale mesopelagic fishery will drive the fishmeal price below $1000/t (Figure 7), leading to negative profits in the mesopelagic fishery (Figure 8). Furthermore, the price drop will make the high-cost production system (Europe) lose profitability (Figure 9). An important point is that a sharp increase in fishmeal supply triggered by the mesopelagic may cause market disturbance and significant negative impacts on existing fisheries. Thus, to meet future growth in fishmeal demand and avoid large/abrupt market disruptions, a slow buildup of the mesopelagic fleet will be less impactful.

5 | CONCLUSIONS AND FUTURE OUTLOOK

The existing bioeconomic studies on future fishmeal supply have focused on the current production systems (Merino et al., 2010; Mullon et al., 2009), our study extends this literature by providing insights into the ways the systems may be impacted by the introduction of a new

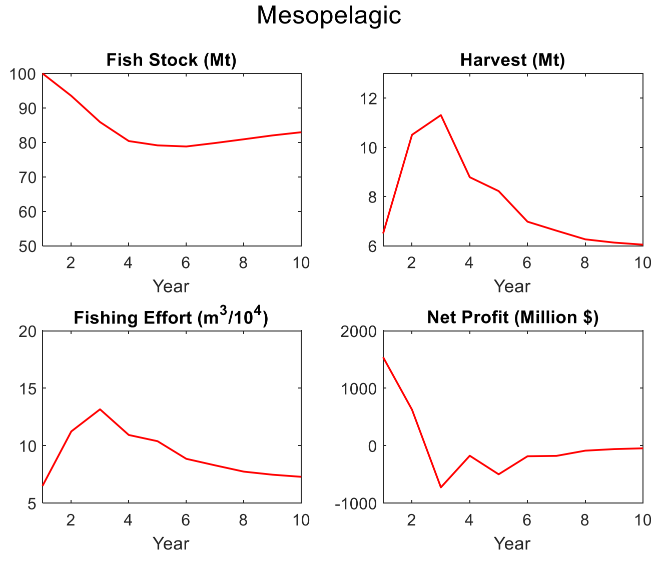

FIGURE 8 Sensitivity analysis: the mesopelagic fishery under a steeper sloped demand curve (compared with the baseline).

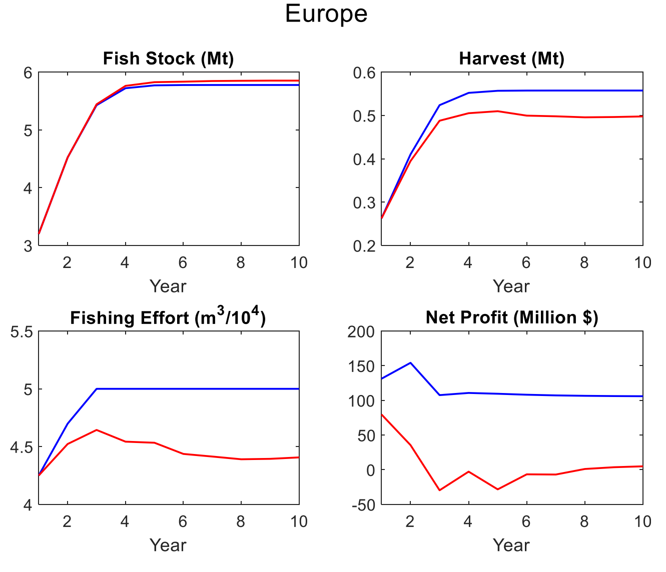

FIGURE 9 Sensitivity analysis: European forage fishery under a steeper sloped demand curve (compared with the baseline). The blue line denotes trajectory without the mesopelagic fishery (Scenario 1). The red line denotes trajectory incorporating a mesopelagic fishery (Scenario 2).

source for fishmeal from a mesopelagic fishery. This responds to the growing interest in the commercial exploitation of mesopelagic fish for supplying the aquaculture industry and the need to understand the trade-offs present alongside potential shifts in global market dynamics. Understanding these shifts, trade-offs and possibilities is instrumental to determining the key components that feed into decision making and policy design for managing these fisheries into

the future. Although technological, economic, and knowledge constraints have thus far largely limited the success of attempts to harvest mesopelagic fish at a commercial scale, the pressure to expand aquaculture production for meeting the world's nutritional needs (FAO, 2022; HLPE, 2014; Merino et al., 2012) and the subsequent pressure for novel and more efficient sources of aquafeeds is opening the way to overcome these constraints. This work therefore contributes to a growing body of literature that assesses the economic viability of the potential development of a commercial-scale mesopelagic fishery (Kourantidou & Jin, 2022; Paoletti et al., 2021; Prellezo, 2019). Prior research has predominantly concentrated on assessing economic viability at regional levels, examining various scenarios, trade-offs, and associated opportunity costs using technical, financial, and market analyses, alongside simulations of current fisheries and their dynamics (Paoletti et al., 2021; Prellezo, 2019; Vastenhoud et al., 2023), as well as ecological–economic interactions with epipelagic fisheries (Kourantidou & Jin, 2022). Our work here introduces the fishmeal market dimension that drives incentives for the commercial exploitation of mesopelagic fish and explores economic viability implications through this lens, including implications to global fishmeal production systems. This is particularly timely as technological barriers recede and conservation policies are considered to ensure that key ecosystems services provided by mesopelagic ecosystems, will not degrade as a result of commercial exploitation (St. John et al., 2016). While the science community is still working on understanding fundamental processes in the Ocean Twilight Zone such as the biological carbon pump, or food web dynamics, among others, policy makers need to be prepared to manage any emerging commercial activities and understand the human and economic drivers of such activities.

This type of analysis has space for improvement to inform with more accuracy the patterns expected for mesopelagic commercial exploitation based on market dynamics, needs for fishmeal production and trends in existing productions systems. For example, going beyond the regions assessed and encompassing the global fishmeal production (beyond the ~70% captured here) could help provide more granular detail to the price and production dynamics alongside their trajectories following the introduction of a mesopelagic fishery. Incorporating additional cost components related to fleet or fishing operational details could also lead to different fishing efforts and net profits. Biological and ecosystem interactions may also affect outcomes and should be incorporated in future exercises of this type, through for example assessing how the introduction of a new mesopelagic fishery may affect the pelagic production system (i.e., considering any prey-predatory relationship and other food web interactions). While here we model them as separate ecological and technical units, in practice spatial use conflict may be present between pelagic and mesopelagic fleets or also synergies so that the same fleet harvests both pelagic and mesopelagic fish, that is, during different seasons and/or different technological/gear equipment for harvest and storage. Depending on the time horizons assessed, climate variations and their effects on stock level may also need to be incorporated for a more accurate picture of the trends expected.

The simple framework provided here to build a basic understanding of trade-offs and market dynamics of fishmeal production can be advanced by capturing more complexity of the fishery systems and incorporating some of the aforementioned details into the model. Nevertheless, these fundamental insights into how stocks, harvests, fishing effort and net profits shift with the addition of mesopelagic fish as a source of fishmeal, are necessary for understanding what to expect from fisheries and aquaculture stakeholders in the future and for informing policy accordingly. The (large) size of the mesopelagic fish biomass alone and the desire to utilize this untapped resource to cover the aquaculture industry's needs are not

enough to inform whether and how this can become a reality considering the current fishmeal market conditions. Indeed, more carefully designed scientific evaluations of social economic and ecological effects associated with resource exploitation in the mesopelagic zone are much needed for the development of an effective governance framework for this important marine ecosystem (Schadeberg et al., 2023).

AUTHOR CONTRIBUTIONS

Rohan Gowda Thanh Quang: Conceptualization; writing—original draft; software; writing—review and editing; formal analysis. **Melina Kourantidou**: Conceptualization; writing—review and editing; validation; formal analysis. **Di Jin**: Conceptualization; funding acquisition; writing—review and editing; software; formal analysis; project administration; data curation; supervision; methodology; investigation; validation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Melina Kourantidou http://orcid.org/0000-0001-9595-3354
Di Jin http://orcid.org/0000-0002-6403-7983

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APPENDIX

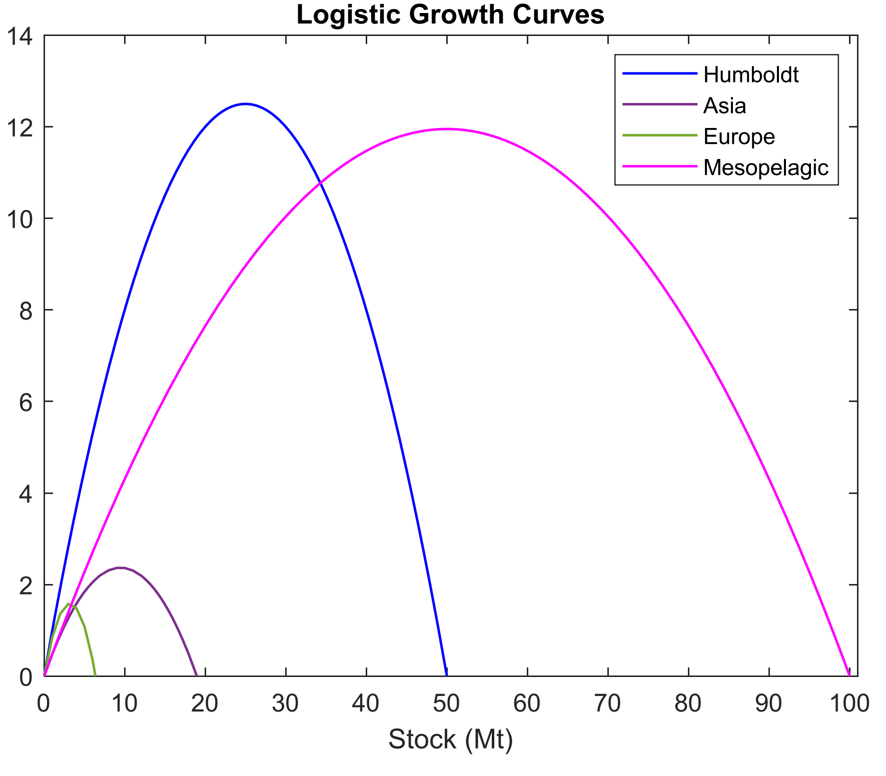

FIGURE A1 Logistic growth functions for the four forage-fish production systems.

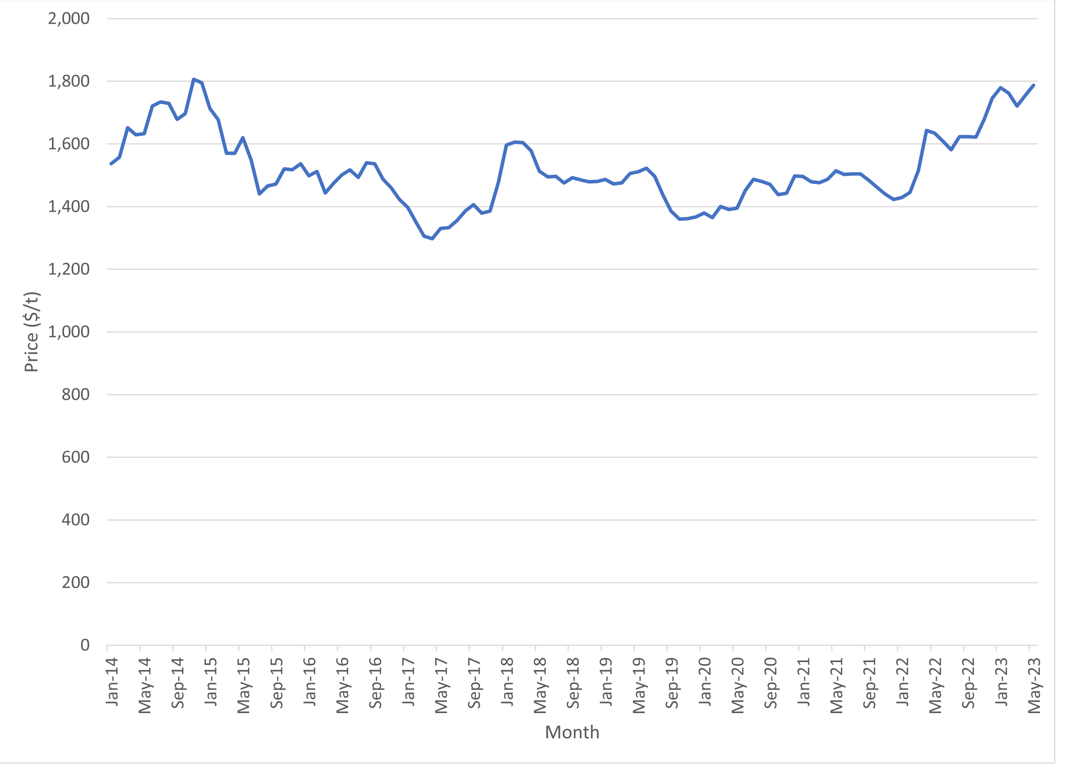

FIGURE A2 Monthly fishmeal price (2014–2023). *Source*: IndexMundi compilation of World Bank data. https://www.indexmundi.com/commodities/?commodity=fish-meal&months=240.

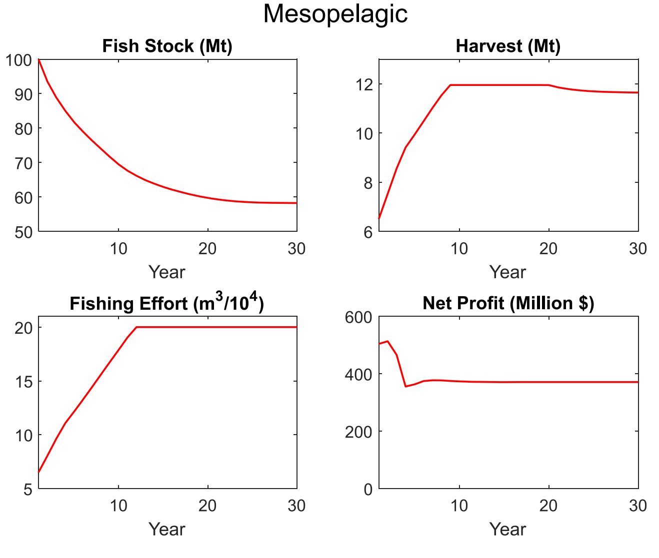

FIGURE A3 Simulation results for the mesopelagic fishery: 30-year horizon.