ICES Journal of Marine Science, 2024, Vol. 81, Issue 8, 1620–1631
https://doi.org/10.1093/icesjms/fsae108
Received: 27 November 2023; **revised:** 23 July 2024; **accepted:** 25 July 2024
Advance access publication date: 12 August 2024
Original Article

Climate damage from fishing the mesopelagic zone exceeds its economic benefits

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Abstract

Mesopelagic fish represent an opportunity for fishing companies and food production, but their exploitation carries substantial environmental risks related to these populations' role in the oceanic carbon pump. We assess the economic viability of mesopelagic fishing from a private economic perspective, focusing on costs and revenues accruing to the fishing industry, and a public economic perspective, considering impacts on society at large, notably climate change. We develop a stylized model, which we apply to four pelagic trawling fleets in the European Union. We find that a mesopelagic fishery operated with current excess capacity in the four fleets considered is profitable from a private perspective, but the climate impacts potentially outweigh the private economic benefits. This implies that strict governance arrangements are needed to safeguard the sustainability of the mesopelagic zone. Considering long-term dynamics, we explore potential natural limits to an expanding mesopelagic fishery. First, a growing fishery will reduce biomass level, affecting profitability. Second, an increase in mesopelagic production may lower the price, also limiting potential for expansion. For the time being, however, it is unlikely that the fishery will reach a scale level where such feedbacks can be expected, making effective governance arrangements even more crucial.

Keywords: mesopelagic; economics; cost-benefit analysis; climate; Denmark; Spain; Ireland

Introduction

Demand for seafood has been rising steadily and is projected to rise further in the foreseeable future (OECD and Food and Agriculture Organization of the United Nations 2023). Main drivers behind this trend are not only population growth, but also general dietary changes driven by increasing affluence and health concerns (OECD and Food and Agriculture Organization of the United Nations 2019).

As wild catches have grown only very slightly in the past decades, the vast majority of projected growth in seafood production will be driven by expansion of aquaculture (Costello et al. 2020, OECD and Food and Agriculture Organization of the United Nations 2023). In turn, this expansion can enhance pressure on wild-capture populations as major aquaculture species such as shrimp, salmon, and trout depend on fishmeal and fish oil (Naylor et al. 2021). Increasing use of trimmings and plant-based feeds has greatly reduced forage fish dependency (Ytrestøyl et al. 2015). Nevertheless, a sizeable proportion of catches, 16×10^6 out of 157×10^6 tonnes of wild capture fish in 2020 (FAO 2022), is reduced to fish meal and fish oil. About 90% of fish caught for reduction are food-grade fish species such as Peruvian Anchoveta (*Engraulis ringens*), Pacific sardine (*Sardinops sagax*), and Atlantic herring (*Clupea harengus*) (Cashion et al. 2017).

In recent years, the mesopelagic zone has received increasing attention as a potential source of fish for fishmeal and fish oil (Valinassab et al. 2007, St. John et al. 2016, Prellezo 2019, Grimaldo et al. 2020). Also called the ocean twilight zone, the mesopelagic zone lies at 200–1000 m depth, where some light still penetrates but insufficiently so to support photosynthesis (Costello and Breyer 2017). It is characterized by zooplankton and fish communities of sufficient density to have been mistaken for seabed echoes in the past (Proud et al. 2017). The total mesopelagic biomass has been estimated at $11–15 \times 10^9$ tonnes (Irigoien et al. 2014).

Fisheries on mesopelagic populations have existed in various parts of the world, but so far none has proven to be economically sustainable. In the 1980s, the Soviet Union maintained a heavily subsidised fishery on Antarctic krill (*Euphausia superba*) and lanternfish (*Electrona carlsbergii*, *Electrona antarctica*), which ended after the Soviet Union's collapse (Payne and Hoagland 2022). Around the early 2010s, Icelandic fishers fished for Mueller's pearlside (*Maurolicus muelleri*), but ended this practice in 2016 (Prellezo 2019). More recently, the Norwegian fishing industry has shown an interest in fishing mesopelagic species such as *M. muelleri* (Fjeld et al. 2023) and glacier lanternfish (*Benthosema glaciale*) (Klokeide 2017), and the economic viability of fishing mesopelagic populations has been assessed for Spain (Prellezo 2019) and Denmark (Paoletti et al. 2021, Vastenhoud et al. 2023).

A mesopelagic fishery faces challenges related to depth, mesh size, and catch preservation. Trawling at a depth of up to 400 m with a mesh size of around 10 mm (Valinassab et al. 2007, Grimaldo et al. 2020, Andrés and Álvarez 2021), fuel consumption is likely to be high (Paoletti et al. 2021). Moreover, because of the rapid chemical and biological breakdown (putrefaction) of harvested fish (Andrés and Álvarez 2021, Paoletti et al. 2021), vessels would need adequate preservation facilities, such as refrigerated sea water (RSW), and fishing trips would be limited to 3–5 days. Longer trips would require more advanced facilities such as a silage system or on-board processing into fish meal and fish oil (Andrés and Álvarez 2021).

Because of these challenges, it is uncertain whether a mesopelagic fishery would currently be economically viable. Prellezo (2019) finds that fishing the mesopelagic in the Bay of Biscay is currently not a viable alternative to existing fisheries, unless the landing obligation under the European Union's Common Fisheries Policy (European Union 2015) drastically reduces its opportunity costs. Paoletti et al. (2021) find for the Danish pelagic fleet that a mesopelagic fishery would require a minimum average catch of 220–1060 tonnes per trip to be viable. A follow-up study by Vastenhoud et al. (2023) estimates for the large-scale Danish pelagic fishery that a profitable mesopelagic fishery would require a fish price twice that associated with other, similar species. Nevertheless, as demand for fishmeal is expected to increase (OECD and Food and Agriculture Organization of the United Nations 2023) and more efficient catching and onboard processing technologies may emerge, a mesopelagic fishery might one day become profitable.

The ecological risks associated with mesopelagic fishing, however, imply that a fishery that is economically viable from the perspective of an individual fishing company might not be desirable from a societal perspective (Martin et al. 2020). A number of important epipelagic species, such as albacore tuna, feed on mesopelagic fish populations (Duffy et al. 2017), and stocks of these higher trophic level species might be affected by a fishery on those same resources (Dowd et al. 2022, Kourantidou and Jin 2022). Potentially much more serious, however, is the impact that a fishery on mesopelagic populations could have on the global climate system. Many mesopelagic fish species, including the commercially targeted *M. muelleri* (Staby and Aksnes 2011) and *B. glaciale* (Dypvik et al. 2012), forage in upper layers at night while staying in deeper layers at day to avoid visual predators, a process referred to as diel vertical migration. In doing so, these fish transport organic carbon to deeper layers as they respire, excrete faecal pellets, and die (Saba et al. 2021, Siegel et al. 2023). Estimates of the scale of carbon export mediated by vertically migrating mesopelagic fish range between 0.6 and 3.4 Pg C yr^{-1} (Saba et al. 2021). Therefore, exploiting these populations arguably could seriously disrupt an important part of the oceanic carbon pump. Concerns over its ecological impacts have inspired calls for a global moratorium on fishing the mesopelagic (Roberts et al. 2020). Indeed, in the US Pacific Exclusive Economic Zone (EEZ), such a policy is already in place (Pacific Fishery Management Council 2019). Jin et al. (2020) estimate the economic value of research on the biological carbon pump but do not consider the impact of a fishery.

Hence, the question how to govern mesopelagic fishing is surrounded by multiple uncertainties. For an evidence-based fisheries policy, there are two important questions that need to be resolved. First, how profitable is mesopelagic fishing from a private, i.e. fishing industry perspective? On the one hand, if commercial exploitation of the mesopelagic zone is very profitable, fishing pressure is likely to be high, which calls for governance frameworks. On the other hand, if mesopelagic fishing is unprofitable, sophisticated governance arrangements are probably redundant. Second, how desirable is mesopelagic fishing from a societal perspective? If mesopelagic fishing is creating negative impacts, for example, on the ocean's carbon pump, policies regulating the mesopelagic zone may have to be much more restrictive than in absence of such impacts.

In this article, we explore the economic viability of mesopelagic fishing from two perspectives: (1) that of private fishing companies; and (2) that of society at large. In the first perspective, we assume a small, nascent fishery, operating with existing equipment. This is a plausible scenario for early stages of development of mesopelagic fishing by a fishery with excess capacity. We focus on four fishing fleets in EU member states that have been considered in earlier economic analyses of mesopelagic fishing, because these analyses suggest that at least these fisheries might be considering to explore a mesopelagic fishery, and economic data on these fisheries are publicly available (STECF 2021). In the second perspective, we extend the analysis to include not only private costs and benefits, but also public costs, notably climate impacts through greenhouse gas emissions and impacts on fish-mediated carbon export. Assuming a small, nascent fishery allows us to focus on the marginal impact when the biomass is close to its carrying capacity, so that the marginal impact of fishing can be assumed independent of carrying capacity or current biomass. Finally, we extend the analysis of a small, nascent fishery by exploring two potential natural limits on a larger mesopelagic fishery: lower catch per unit effort due to stock effects; and lower fishmeal prices due to increased supply.

The paper proceeds as follows: Section 'A stylized model of fishing the mesopelagic' explains a general bioeconomic model of a single-species mesopelagic fishery that includes climate externalities through fossil fuel combustion and reduced oceanic carbon flux, and Section 'Model parameterization' explains the parameterization of the model. In Section "Small' fishery limited by current capacity', we use this model to analyse the viability conditions for a nascent mesopelagic fishery, i.e. one limited by current fishing capacity. Section 'Limits to growth in mesopelagic fishing' reflects on the possible limits to growth of the fishery. Section 'Discussion and conclusion' concludes the paper with the general lessons learned.

A stylized model of fishing the mesopelagic

Biology and harvesting

To retain tractability of the analysis, we assume a single species representing the variety of potentially commercial mesopelagic species such as *M. muelleri* and *B. glaciale*. We model the biological dynamics through a standard Gordon-Schaefer growth function:

$$\dot{S} = rS_t\left(1 - \frac{S_t}{k}\right) - H_t \tag{1}$$

where $\dot{S}$ denotes the change of biomass (S_t) over time; r denotes the intrinsic growth rate of the population; k denotes the population's carrying capacity; and H_t denotes harvest of biomass at time t. Harvest is a function of biomass and fishing effort:

$$H_t = qS_tE_t \tag{2}$$

where q denotes the efficiency of the fishery; and E_t denotes fishing effort. In a steady state, $\dot{S} = 0$ and $H_t = rS_t(1 - \frac{S_t}{k})$.

Climate externalities

We include two pathways for the impact of a mesopelagic fishery on global greenhouse gas concentrations: (1) combustion of fossil fuels, notably diesel; and (2) its impact on populations of vertically migrating mesopelagic fish. Hence, net emissions from a mesopelagic fishery are expressed as:

$$G_t = fE_t + g\left(k - S_t\right) \quad (3)$$

Where G_t denotes greenhouse gas emitted at time t; f denotes greenhouse gas emissions through combustion of fossil fuel per unit of fishing effort; and g denotes the carbon sequestration per unit of biomass removed from the population.

Economics

Private economic net benefits are included as profits, which are equal to

$$\pi_t = PH_t - cE_t \quad (4)$$

where π_t denotes fishing profits; P denotes the price of fish; and c denotes the private cost of fishing effort inputs (e.g. labour, taxes, and fuel).

Public economic net benefits differ from the private economic viability in the following respects: (1) climate impacts are expressed through the economic damage inflicted on other parts of the economy, as measured by the social cost of carbon (SCC); and (2) taxes are considered net transfers between the company and the government rather than an expense of resources:

$$W_t = PH_t - c\lambda E_t - \sigma G_t \quad (5)$$

where W_t denotes public economic net benefits; $0 < \lambda < 1$ accounts for the fact that taxes paid by fishing companies are a cost for fishing companies but a revenue to government, i.e. transfers with no net welfare impact; and σ denotes the societal damage inflicted by net greenhouse gas emissions.

Model parameterization

Parameter values in the break-even analysis

The break-even analysis requires estimates of the population's intrinsic growth rate (r), the catch rate (qS_t), the amount of carbon export forgone per reduction in biomass (g), the variable costs (c), the share of income taxes in variable costs ($1 - \lambda$), fuel use (f), the social cost of carbon (σ), and the fish price (P) (Table 1). All these variables are, to some extent, uncertain, but in the break-even analysis we examine the economic viability of mesopelagic fishing under various combinations of catch rate and price (cf. Paoletti et al. 2021, Prellezo 2019), and of the social cost of carbon. Hence, we will explore a range of possible values for these variables, while assuming a specific value for the others.

Biology and harvesting

Estimates of r, k, and q are uncertain as the biology and ecology of the mesopelagic zone are yet poorly understood (St. John et al. 2016, Martin et al. 2020). Nevertheless, the scientific literature on these variables provides helpful clues to ranges that are at least plausible.

Regarding the intrinsic growth rate (r), a starting point is the growth coefficient from the Bertalanffy growth function, which provides the rate at which the asymptotic length is approached and given by 0.88 for *M. muelleri* (Gjøsaeter and Kawaguchi 1980). However, this coefficient represents individual growth, while population growth would require also incorporating net reproduction. Following Farkas (2001), the intrinsic growth rate can be inferred from the generation doubling time T, where $r = (\ln 2)/T$. Froese et al. (2017) suggest that a plausible range for the generation doubling time for *M. muelleri* is between 1.4 and 4.4, yielding a range for r between 0.95 and 3.05.

Global estimates of population size for mesopelagic fish vary by almost an order of magnitude, from 2.4×10^9 tonnes (Anderson et al. 2019) to >11–15×10^9 tonnes (Irigoien et al. 2014). In the Bay of Biscay, Sobradillo et al. (2019) estimate that biomass varied between 70.8 and 161.7 thousand tonnes in 2014–2017. Hence the carrying capacity (k) is uncertain, which makes estimates of the catch coefficient (q) also difficult to obtain.

Nevertheless, past experimental fisheries so far (Valinassab et al. 2007, Marine Research Institute 2016, Grimaldo et al. 2020, Standal and Grimaldo 2020, Andrés and Álvarez 2021) give some clue to potential catch rates per fishing day, which would be qS_t in Equation (2). Experimental trawls on skinnycheek lanternfish (*Benthosema pterotum*) in the Oman Sea in 1993–1998 attained average catch rates around 25 tonne per day (Valinassab et al. 2007). The 2008–2011 Icelandic mesopelagic fishery saw landings of *M. muelleri* of 46 195 tonnes in 2009, although catches quickly declined to 9109 tonnes in 2012 and practically ceased after that except for incidental landings in 2014 and 2019 (Fiskistofa, 2022). Catch rates varied between 5 and 25 tonne per hour of trawling (Andrés and Álvarez 2021). Assuming three daily sets of six hours each, Andrés and Álvarez (2021) estimate the daily catch rate at a maximum of 275 tonne per day. Standal and Grimaldo (2020), however, report Icelandic catch rates of up to 560 tonnes per day. Experimental trawls by Grimaldo et al. (2020) find catch rates between 0 and 200 kg per minute trawling, although the vast majority of trials (21 of 24) had catch rates below 35 kg per minute. Assuming eight daily sets of 45 minutes for the Irish trawling fleet, Curtin and Gallagher (2021) conclude from these figures that catch rates in this fleet are potentially up to 100 tonnes per day. All in all, catch rates are still very uncertain, with the highest catch rates (560 tonnes per day) reported so far by the Icelandic experience. To be on the safe side, we explore a somewhat larger range between 0 and 800 tonnes per day, but the most plausible catch rates are probably between 100 and 200 tonnes per day.

Forgone carbon export

Various estimates of carbon export by mesopelagic fish are available in the literature (Ariza et al. 2015, Saba et al. 2021, Siegel et al. 2023). Most available estimates, however, regard average carbon flux per m^2 per day, while our analysis requires an estimate of the carbon flux per unit of biomass. Davison et al. (2013) is the only study reporting carbon flux per unit of biomass, which it estimates at 8.31 mg C per day for a 1-g fish in colder waters, or 3 kg C y^{-1} kg^{-1}. About 54.1% of vertically migrating biomass stays below 150 m, so 1.39 kg C y^{-1} kg^{-1} might be a closer estimate for the population as a whole. Considering the molecular weight of carbon (12) and oxygen (16), 1 tonne of carbon is equivalent to $44/12 \approx 3.67$

Table 1. Parameter values in the break-even analysis.

Parameter	Explanation	Value[1)]	Source
r	Intrinsic growth rate	1.5	Froese et al. (2017)
qS_t	Catch rate	0–800 t/d	Valinassab et al. (2007); Marine Research Institute (2016); Grimaldo et al. (2020); Standal and Grimaldo (2020); Andrés and Álvarez (2021)
g	Forgone carbon export from a reduction in biomass	5.1 kg CO_2 y^{-1} kg^{-1} biomass	Davison et al. (2013)
c	Variable costs Danish large-scale pelagic	21.3 k€ DAS^{-1}	Paoletti et al. (2021); STECF (2021)
	Variable costs Irish RSW	30 k€ DAS^{-1}	STECF (2021)
	Variable costs Spanish PTB	3.8 k€ DAS^{-1}	STECF (2021)
	Variable costs use Spanish COD	13.9 k€ DAS^{-1}	STECF (2021)
λ	Tax correction factor Danish large-scale pelagic	0.86	STECF (2021); OECD (2022)
	Tax correction factor Irish RSW	0.84	STECF (2021); OECD (2022)
	Tax correction factor Spanish PTB	0.83	STECF (2021); OECD (2022)
	Tax correction factor Spanish COD	0.83	STECF (2021); OECD (2022)
f	Fuel use Danish large-scale pelagic	12.3 m^3 DAS^{-1}	Paoletti et al. (2021); STECF (2021)
	Fuel use Irish RSW	10.7 m^3 DAS^{-1}	STECF (2021)
	Fuel use Spanish PTB	2.6 m^3 DAS^{-1}	STECF (2021)
	Fuel use Spanish COD	5.7 m^3 DAS^{-1}	STECF (2021)
σ	Social cost of carbon	€89–182 $tonnes^{-1}$ CO_2-eq	Hänsel et al. (2020)
P	Fish price	€0–600 $tonnes^{-1}$	EUMOFA (2021); Paoletti et al. (2021)

[1)]DAS = Day-at-sea

tonne of CO_2. This suggests that the forgone carbon export from reducing biomass by one kg (g) is equivalent to about 5.1 kg CO_2 y^{-1}.

Variable costs, income tax rates, and fuel use

We focus our analysis on the Irish RSW fleet (Curtin and Gallagher 2021); the Danish pelagic trawling fleet (Paoletti et al. 2021, Vastenhoud et al. 2023); and the pair trawler and cod trawler fleets based in the Basque Country, Spain (Prellezo 2019, Andrés and Álvarez 2021). For our estimate of variable costs, we take the median of variable costs over 2008–2020 as reported in the 2021 Annual Economic Report of the Social, Technical, and Economic Committee on Fisheries (STECF 2021). These estimates are assumed to be representative for a mesopelagic fishery by each of the fleets considered, except for the Danish midwater trawls. The variable costs in the Danish midwater trawl fishery vary widely according to the target species (Paoletti et al. 2021). Paoletti et al. (2021) report for the Danish midwater fishery that fishing the mesopelagic would most resemble the blue whiting fishery, whose variable costs can be up to three times those of the other fisheries in the Danish fleet segment. Comparing variable cost estimates for the Danish blue whiting fishery with STECF estimates for 2016 and 2017 suggests that total variable costs per day-at-sea are 20% to 30% higher for the blue whiting fishery than for the Danish large midwater trawling fleet as presented in STECF data. We therefore assume that for Denmark, median costs and fuel use are 25% higher than the estimates in Table 2.

The share of income taxes in the costs of fishing effort $(1 - \lambda)$ is estimated through the respective countries' tax wedge (OECD 2022) and labour costs according to STECF (Table 2).

Fuel use per fishing day (f) is estimated from STECF data (Table 2); we use the estimate of 2.72 kg CO_2-eq per litre of the Australian National Greenhouse Accounts Factors (Australian Government 2021) to convert these figures to greenhouse gas emissions per fishing day.

Social cost of carbon

Economic damage from GHG emissions and forgone sequestration is estimated by the Social Cost of Carbon (SCC) (Tol 2011). Estimates of the SCC vary widely, from negative to more than 800 US$ per tonne CO_2 (Tol 2008, 2018, Wang et al. 2019). Matthey and Bünger (2019) recommend using a SCC of €180 per tonne CO_2 for 2016, but also recommend sensitivity analysis with €640 per tonne CO_2. Based on a range of expert views of the social discount rate (Drupp et al. 2018), Hänsel et al. (2020) estimate the 95% interval of the SCC in 2020 at 21–528 US$ per tonne CO_2, with a median of US$101 or US$208, depending on how specific details of the discounting are treated. We use these estimated medians in our analysis.

Fish price

As mesopelagic harvests have so far been limited, direct information on prices is scarce. Trial fisheries in Norway in 2019–2020 fetched a price between €300 and €400 per tonne for *M. muelleri*; Danish pelagic fishing industry representatives expect landing prices to be similar to those of summer herring, which suggests a price between €300 and €550 per tonne (Paoletti et al. 2021).

Looking at other reduction fish prices, EUMOFA (2021) reports first-sale prices of €190–280 per tonne from 2007 to 2020 for sprat, and €380–730 per tonne for herring. STECF data suggest slightly lower prices (Fig. 1), but these prices are transfer prices rather than market prices for a large part of the industry, so they could be an underestimate of the market price. Blue whiting prices are not reported by EUMOFA (2021), and in STECF data they fluctuate strongly but have remained below €400 per tonne since 2015. Similar to our

Table 2. Key variables [minimum-median-maximum over 2008–2020 estimated from STECF (2021) and OECD (2022)] for the fleets analysed in this study.

	Denmark	Ireland	Spain -Pair trawlers (PTB)	Spain—Cod trawlers (COD)
Fishing technology (trawl)	Midwater	Midwater	Demersal	Demersal
Vessel length (m)	>40	>40	24–40	>40
Number of vessels	11–15.5–22	19–20–21	94–140–244	13–17–42
Tonnage per vessel	1152–1481-1937	1052–1130–1360	254–259–269	1011–1068–1352
Top-3 species in terms of revenue in 2019	Atlantic herring (40.4%); Atlantic mackerel (23.6%); European sprat (15.1%)	Atlantic mackerel (65.3%); Jack and horse mackerels nei (16.9%); Blue whiting (12.8%)	European hake (12.7%); Striped red shrimp (9.1%); Anglerfishes nei (8.1%)	Argentine hake (42.0%); Atlantic cod (13.8%); Greenland halibut (9.0%)
Top-3 FAO catch areas in terms of revenue 2019	27.4.a (40.3%); 27.4.b (29.1%); 27.6.a (11.0%)	27.6.a (71.6%); 27.7.b (16.0%); 27.7.c (2.5%)	27.8.c (17.5%); 34.3.1 (14.5%); sa 6 (14.0%)	41.3.2 (30.5%); 41.3.1 (26.8%); 27.2.b (7.2%)
Fuel use (m^3/day)	7.9–9.8–12.1	6.2–10.7–28.9	1.9–2.6–3.3	3.4–5.7–6.7
Private variable costs (2015 kEUR/DAS[a])	15–17–19.7	14–30–41.2	2.5–3.8–4.5	7.4–13.9–18
Income tax (2015 kEUR/DAS[a])	2.3–2.6–2.8	1.6–4.8–6	0.5–0.6–0.8	1–2.5–3.9

[a]DAS = Day-at-sea We selected four fishing fleets in EU member states that have been considered in earlier economic analyses of mesopelagic fishing.

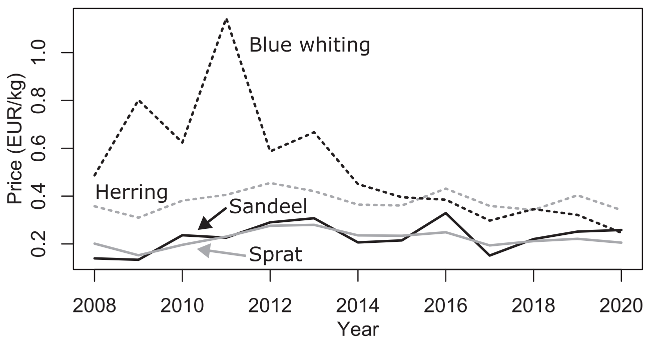

Figure 1. Average landing prices (in 2015 EUR prices) in EU member states, estimated from STECF landing value and weight data.

range of potential catch rates, we explore a rather wide range of fish price estimates between €0 and €600 tonne^{-1}.

'Small' fishery limited by current capacity

Potential scale

We investigate whether a mesopelagic fishery would be economically viable from a private and a public perspective in a steady state limited by current fishing capacity. In other words, we assume that the fisheries use only current fishing capacity and that they do so long enough for a steady state to establish. To assess the potential scale of the fishery in this scenario, we need to consider what excess capacity is currently available in the four fleets considered.

The Danish pelagic trawling fleet currently operates at full capacity, and it is unlikely to replace even its least profitable species by mesopelagic species (Paoletti et al. 2021). In Spain, the Basque cod trawling fleet has some excess capacity that it might use to fish mesopelagic resources. It currently consists of two vessels, which have no fishing activity for seven months per year (Andrés and Álvarez 2021). Using RSW to conserve the catch would allow for fishing trips up to three days, whereas longer trips would require more advanced onboard conservation or processing technologies such as ensiling or conversion to fish meal and fish oil (Andrés and Álvarez 2021). One three-day trip per week could potentially amount to about 90–100 fishing days per year per vessel. With the maximum catch rate of 275 tonne per day estimated in Andrés and Álvarez (2021), this would amount to a maximum of 55 000 tonne per year. The Irish pelagic refrigerated seawater fleet consists of 24 vessels, which are inactive during the months of May, June, July, and August (Curtin and Gallagher 2021). In the months that the fleet is active, a vessel fishes on average 73 days per year; the same intensity in the other months would amount to 36–37 fishing days in May-August. If we assume the potential catch rate of 100 tonne per fishing day (Curtin and Gallagher 2021), this number of fishing days for the entire fleet would amount to a maximum of 88 800 tonne per year. Altogether, the potential mesopelagic catch that can be achieved with current excess capacity in the four fleets considered would be in an order of 140 000–150 000 tonne per year.

Private economic viability

The assumption of a small, nascent fishery implies that the harvest is small compared to the overall population, which implies that the stock of biomass remains close enough to the carrying capacity to assume a constant catch rate per day-at-sea ($m := qk$) rather than using separate values of q and k with empirical catch rates (Grimaldo et al. 2020, Standal and Grimaldo 2020, Andrés and Álvarez 2021, Curtin and Gallagher 2021). Considering the experience with experimental trials so far, we explore a range of 0–800 tonnes per fishing day.

Following Paoletti et al. (2021), we estimate the break-even curve (BEC) for the relevant Danish, Irish, and Spanish fishing fleets. We define the BEC as the curve depicting all combinations of catch rate and price that are just sufficient to recover the costs of fishing. All combinations of catch rate and price above the BEC imply an economically viable fishery, whereas all those below the BEC imply a fishery that is unable to recover its fishing costs. Our analysis differs from that of Paoletti et al. (2021) on two major points.

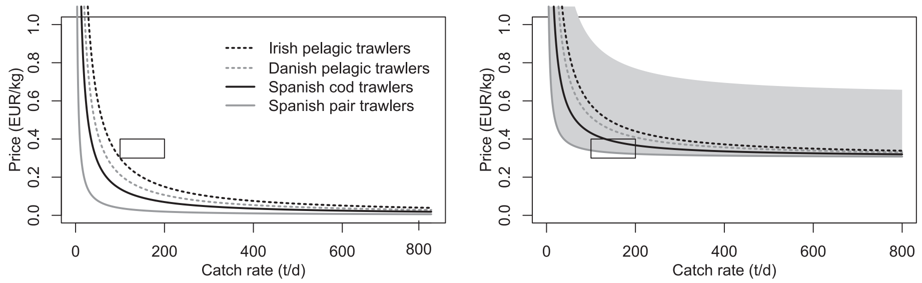

Figure 2. Break-even prices as a function of catch rate for Danish pelagic trawlers, Irish pelagic trawlers, Spanish pair trawlers, and Spanish cod trawlers. The black square indicates the combination of prices as experienced by the Norwegian trial fisheries (€300-€400 per tonne), and a catch rate of 100–200 tonne per day. Left: private perspective; right: public perspective under a growth rate (*r*) of 1.5 and social cost of carbon between €89 (bottom of shaded area) and €182 (top of shaded area) per tonne CO_2-eq.

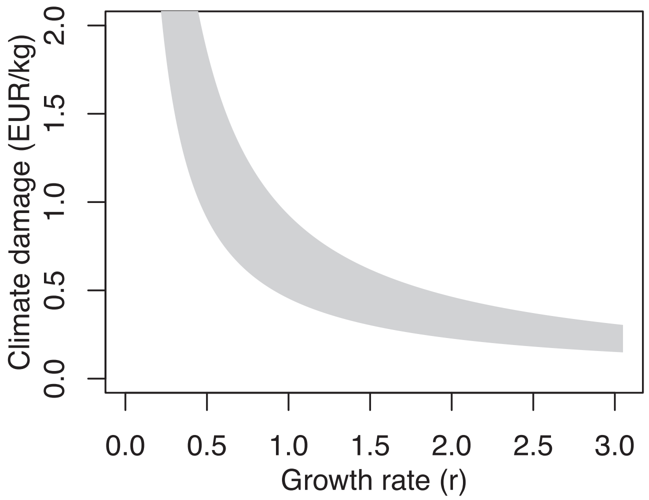

Figure 3. Climate damage (€ per kg catch) as a function of the intrinsic growth rate. The shaded area shows the width of values between Hänsel et al.'s (2020) estimates of the median social cost of carbon (€89 and €182 per tonne CO_2, respectively).

First, whereas Paoletti et al. (2021) focus on the long-term economic viability of fisheries operations, i.e. taking into account fixed costs such as depreciations, we focus on a scenario where such fixed costs are 'sunk' as fishing companies use existing capacity. Hence, we focus on the variable costs, assuming that variable costs are indicative of the marginal costs of fishing. Second, whereas Paoletti et al. (2021) estimate the BEC per fishing trip, we do so per fishing day in order to allow for comparison between the respective fishing fleets.

In this scenario the fishery is economically viable if revenues exceed variable costs:

$$PH > cE \Rightarrow PmE > cE \Rightarrow P > \frac{c}{m} \tag{6}$$

The left panel in Fig. 2 shows the break-even prices for the four fleets, as a function of catch rate. Intuitively, if the price is low, the catch rates need to be high for the fishery to be profitable. By and large, with prices as experienced by the Norwegian trial fisheries (€300-€400 per tonne) and a catch rate of 100–200 tonne per day (indicated by the square in the figure), and no opportunity costs, a mesopelagic fishery seems potentially viable for all fleets considered.

Public economic viability

We now introduce public costs in the analysis and find that the impact of fishing on mesopelagic carbon export is likely to exceed potential commercial benefits. We still assume a small, nascent fishery so that the marginal impact of fishing on carbon export is equal to the marginal impact of the very first unit of harvest. Under this assumption, we derive the impact of harvests on steady-state populations and thereby the steady-state impact on oceanic carbon sequestration. As shown in Appendix A, the marginal forgone oceanic sequestration (MFOS) can be simplified to g/r. For example, with the aforementioned estimate of 5.1 kg CO_2-eq per kg reduction in biomass and a growth rate (r) of 1.5, this expression for the MFOS would mean that catching one tonne of vertically migrating mesopelagic fish every year reduces annual oceanic carbon sequestration by about $5.1/1.5 = 3.4$ tonne CO_2-eq. If we take Hänsel et al.'s (2020) lower estimate of the median SCC (US$101), the monetary value of these emissions would amount to about US$343, or €301 using the 2020 exchange rate of €87.70 to US$100. Fig. 3 shows the bandwidth of climate damage in € per kg catch as a function of the growth rate (r) with a SCC ranging between the medians estimated by Hänsel et al. (2020), converted to EUR with the 2020 exchange rate. The bottom and top of the shaded area in this figure correspond to Hänsel et al.'s (2020) median SCC of US$101 or US$208 (€89 and €182), respectively. The growth rate is uncertain, but the figure shows that even a growth rate between 2 and 3 is potentially associated with climate damages between €149 and €464 per tonne of catch. Growth rates below 1 are associated with much higher climate damage.

Taking these impacts into account, the public BEC is defined by the catch rate and prices at which public economic net benefits (W) are positive. Based on Equation (5), we express this condition as:

$$W > 0 \Rightarrow PmE > c\lambda E + \sigma fE + \sigma \frac{g}{r} mE \Rightarrow$$

$$P > \frac{c\lambda + \sigma f}{m} + \sigma \frac{g}{r} \tag{7}$$

The right panel in Fig. 2 shows the break-even prices for the four fleets as a function of catch rate from a public perspective, i.e. correcting for income tax transfers and climate damage, assuming a growth rate (r) of 1.5, and a SCC between €89 and €182 per tonne CO_2-eq. The figure suggests that if prices are below €300–330 per tonne, the social costs are too high for any of the fleets considered to justify exploitation. The black square in the figure indicates prices as experienced by the Norwegian trial fisheries (€300-€400 per tonne), and a catch rate of 100–200 tonne per day. Under these conditions, the revenues from a mesopelagic fishery are unlikely to justify the sum of public costs. These results are solely driven by the climate impacts, which are at least €303 per tonne of catch under these assumptions.

Limits to growth in mesopelagic fishing

We now look beyond the 'small' mesopelagic fishery explored in the previous section to consider two potential limits to a larger-scale mesopelagic fishery: ecological feedback through reduced stock abundance; and economic feedback through reduced fishmeal prices.

Investment dynamics

In the short run, fishing capacity is constrained by current vessels in operation that have excess capacity. In the long run, the fishing industry may invest in new vessels and fishing capacity may increase. We assume, first, that investments will be made if exploiting the mesopelagic zone is profitable. Second, the size of the investments depends on the profitability—if it is very profitable to exploit the mesopelagic zone, we expect to see higher investment in fleet capacity. Third, if it is unprofitable to exploit the mesopelagic zone and companies lose money, fleet capacity will shrink—as retiring vessels will not be replaced or vessels will be removed from the fishery. In the absence of regulation, the investment in fishing capacity can be described by a dynamic open access model where the fishing effort (in tonnage days) changes as follows:

$$\dot{E} = \theta \left(PH_t - cE_t \right), \tag{8}$$

In Equation (6), we established that the fishery is profitable if $P > c/m$ under the assumption that the stock is close to the carrying capacity. Here, we relax this assumption and analyse the coevolution of stock dynamics [Equation (1)) and fleet dynamics (Equation (8)]. Combining Equations (2) and (8) gives the change in fishing effort as

$$\dot{E} = \theta \left(PqS_tE_t - cE_t \right). \tag{9}$$

The fishery is expanding as long as $PqS_t > c$, which implies that any change in those parameters could tip the balance from mesopelagic fishing from being unprofitable to being profitable, i.e. the break-even point. If mesopelagic fishing is viable, the change in stock dynamics will determine the point where mesopelagic fishing will become unprofitable, which is defined by the open access equilibrium where $\dot{S} = 0$ and $\dot{E} = 0$. This implies that investment dynamics are in equilibrium if $S^* = \frac{c}{Pq}$. We can calculate the catchability coefficient by noting that currently the stock of mesopelagic biomass in the oceans is equal to the carrying capacity (assumed to be 10×10^9 tonnes) and catch rates are currently around 150 tonnes per day. Using $q = m/k$ gives then a catchability coefficient equal to 1.5×10^{-8}. If we assume a price of €350 per tonne of harvests and a cost of €17 000 euros per day, the equilibrium biomass will be around 32% of the carrying capacity.

To see what this expansion might mean for climate impacts, we need to loosen the assumption that the catch is 'small' compared to the population's carrying capacity. Equation (16) in Appendix A suggests that marginal impact of fishing on biomass increases with exploitation. This implies that not only do climate impacts increase with mesopelagic catch, the *increase* in impacts with every next unit of harvest also increases.

It is also yet difficult to say what such an upscaled mesopelagic fishery will look like. Currently, the quick deterioration of the catch is one of the most important obstacles to a large-scale mesopelagic fishery (Andrés and Álvarez 2021). Fishing companies and researchers are looking into possibilities to either preserve or process the catch onboard, for example by processing it into fishmeal or fish oil, or by ensiling (Klokeide 2017, Aadland 2018, Olsen et al. 2020). It is difficult to predict which of these solutions will eventually prevail.

The price as a limiting factor

A large-scale mesopelagic fishery may reduce the end prices in the fish meal and fish oil markets, and such price decline can in turn potentially limit the profitability of a mesopelagic fishery. To gain insight into the plausibility of this effect, we need to gain a perspective on the scale and structure of the global market for fish meal and fish oil, trends in conversion rates for fish meal and fish oil, and of the relation between price and production for fish meal and fish oil.

Regarding the scale and structure of the global market for fish meal and fish oil, 18×10^6 tonnes were reduced to fishmeal and fish oil (FAO 2020, pp. 60–61), where Peru (24.0% in 2010), Chile (16.5% in 2010), and China (15.8% in 2010) are clearly the dominant players (Cashion et al. 2017). Hence, the potential short-term catch of about 150 000 tonnes by a European mesopelagic fishery as estimated in Section 'Potential scale' would amount to <1% of global production.

Conversion efficiency of fish to fishmeal in Peru has improved from the late 1980s to the mid-1990s; from the 1990s onwards, the efficiency has been fairly stable between 4 and 4.5 tonnes of raw material to tonnes of fishmeal, which corresponds to conversion rates of 0.25 and 0.222, respectively (Tacon 2009).

Regarding the question how prices depend on supply for fishmeal and fish oil, such prices depend heavily on Peruvian production (EUMOFA 2021), which, in turn, depends heavily on the periodic El Niño climate events. Peruvian prices have typically fluctuated between €0.10 and €0.18 per kg fishmeal and €0.10 and €0.22 per kg fish oil in 2015 prices (EUMOFA 2021).

Figure 4 illustrates the association between fish meal and fish oil prices (logged) and their production (logged) based on annual data from IFFO. The slope of the fitted lines can be interpreted as the elasticity of prices with respect to the production level, which is the percentage change in prices associated with 1% change in the production. While the slope parameters are negative, their size is small. In Appendix B, we present the estimated size of the slope parameter from several regressions with different specifications. In general, the estimated elasticity is below 0.1 indicating that an increase in production levels by 1% is associated with a less than 0.1% decrease in the observed prices. Furthermore, the estimated parameter is never statistically significant, which is also clearly depicted in Fig. 2 with 95% confidence intervals.

These results suggest that the effect of a mesopelagic fishery on world fish meal and fish oil prices is likely to be very small. For example, a catch of 1.5×10^6 tonnes per year, i.e. ten times the current estimated excess capacity in the four countries

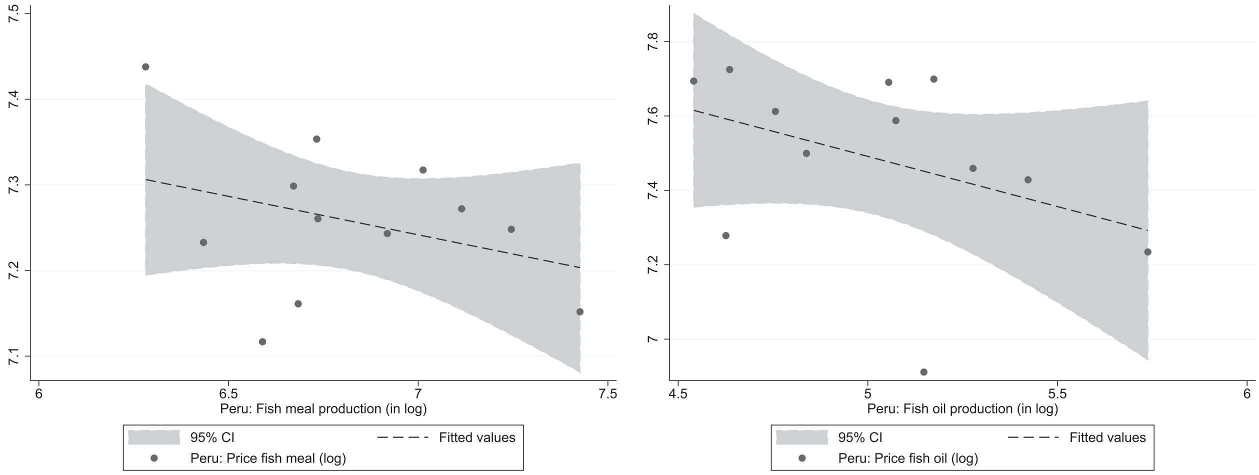

Figure 4. The association between production and prices for Peru.

considered, would amount to an increase of global catches of about 8%. Assuming a conversion rate for *M. Muelleri* and *B. glaciale* similar to other reduction species, this would reduce global fishmeal and fish oil prices by <1%.

Discussion and conclusion

In this article, we assess the private and public economic viability of a fishery on mesopelagic resources. Our approach offers quantitative insights into the costs and benefits of such a fishery while retaining analytical tractability. Nevertheless, the simplicity required to retain such tractability means, unavoidably, that many considerations have been left out.

An important delineation of our analysis is our focus on a fishery whose catches are relatively small compared to the overall stock size. This allows us to assume that catch rates and climate increase linearly in fishing effort and catch, but this assumption will not hold if the fishery is scaled up considerably. As catches increase, catch rates may decline due to lower stock abundance, whereas the marginal impact of catch on biomass, and hence on the oceanic carbon pump, will become more severe. In that respect, our analysis represents a 'best case' scenario for the private and public economic viability of a mesopelagic fishery.

However, our estimate of the climate impact of mesopelagic fishing can also be an overestimate of the true impact, for two reasons. First, the empirical relation between harvest and abundance is found to be weak for small pelagic species due to their high volatility and natural mortality (Hilborn et al. 2022). A high natural mortality could imply that a substantial part of the catch would have died from predation relatively soon if it had not been harvested.

Second, our estimate of the impact of a mesopelagic fishery on the oceanic carbon pump is based on one study (Davison et al. 2013), which to our knowledge is the only study that explicitly reports an estimate of carbon export per unit of biomass. A considerable number of studies have estimated active carbon flux (see, e.g. Hudson et al. 2014, Ariza et al. 2015, Saba et al. 2021, Siegel et al. 2023), but except for Davison et al. (2013), such studies typically report only the carbon flux per m^2; biomass estimates are typically reported in mg C, whereas our study requires biomass estimates in wet weight. Therefore, these studies are difficult to compare to the estimates in our analysis, but Ariza et al. (2015) compare flux estimates (in mg C m^{-2} d^{-1}) as well as biomass estimates (in mg C m^{-2}) of various studies, including that of Davison et al. (2013). Other studies reported in Ariza et al. (2015) have come to much lower estimates of active carbon flux than Davison et al. (2013), while their biomass estimates are comparable or even higher. This suggests that the impact on the oceanic carbon pump assumed in our paper may be exaggerated.

Our analysis does not include the importance of *M. muelleri* and *B. glaciale* for other fish species (Dowd et al. 2022, Kourantidou and Jin 2022). These impacts are outside the scope of this article as we focus on climate impacts, but it is important to reiterate that potential foodweb impacts are another reason to be cautious about fishing mesopelagic resources.

Lastly, our analysis of economic viability does not consider wider, more strategic reasons for fishing companies or countries to start fishing mesopelagic resources. Concerns about food sovereignty led the Soviet Union to financially support a massive and wasteful fishery on Antarctic mesopelagic resources, which collapsed as soon as such support ended (Payne and Hoagland 2022). Another strategic reason to engage in a fishery, even if it is not economically viable in the short term, is to establish a catch history in anticipation of the allocation of catch quota (Copes et al. 2004, Branch 2009).

With these limitations in mind, we can gain the following insights from our analysis. First, in the short term, assuming that fishing companies use current excess capacity, a mesopelagic fishery seems potentially economically viable, particularly for Basque pair trawlers and cod trawlers. The largest capacity appears to be with the Irish pelagic fleet, which is also the fleet with the highest costs, but potentially prices and catch rates could still be high enough to make this fishery economically viable.

When we include the climate impacts of a mesopelagic fishery, however, our analysis suggests that it is very difficult to justify this fishery from a public perspective. The impact on oceanic carbon sequestration from catching one unit of mesopelagic vertically migrating fish, valued by common estimates of the social cost of carbon, is likely to exceed even the market price of the fish.

All these results depend strongly on a range of variables that are yet very uncertain: the population growth rate, the role of

M. muelleri and *B. glaciale* in oceanic carbon sequestration, the social cost of carbon, the catch rate, and the market price. It is possible that our estimate of climate impacts is exaggerated, but considering the uncertainties and the potential climatic risks involved, it seems prudent to proceed with caution. Especially considering that governance arrangements usually tend to take time to be negotiated and crafted, a global unregulated mesopelagic fishery that is evolving without any constraints may pose substantial societal costs that may outweigh the private benefits attached to such fishery. This raises the question whether there are any natural limits to mesopelagic fishing in the absence of governance arrangements. Our exploratory analysis shows little support for such natural limits. Unless fishing fleets are expanded considerably towards mesopelagic fisheries, the scale of a mesopelagic fishery is unlikely to have a noticeable impact on global fishmeal and fish oil markets, which are currently dominated by Chilean and Peruvian catches. Our back-of-the-envelope calculations also suggest that stock effects would make mesopelagic fishing unprofitable only if biomass is fished down to 32% of carrying capacity. Considering that a growing industry may also imply innovations in markets, technology, and value chain, it is certainly not implausible that a mesopelagic fishery—if successful—will also be rather large. Our results therefore suggest that it is important to consider how governance arrangements could be designed and setup to successfully regulate mesopelagic fishing.

Acknowledgements

We thank IFFO-The Marine Ingredients Organization for their kind permission to use IFFO data for this article. Helpful comments from Douglas Spiers, Marga Andrés, Rasmus Nielsen, and two anonymous reviewers are gratefully acknowledged. Any remaining errors are the responsibility of the authors. This work is delivered as part of the Horizon 2020 project MEESO (Ecologically and Economically Sustainable Mesopelagic Fisheries) (2019–2023), grant agreement No 817669.

Author contributions

Rolf Groeneveld (Conceptualization, Methodology, Formal Analysis, Investigation, Data curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Project Administration, Funding Acquisition), Andries Richter (Conceptualization, Methodology, Formal Analysis, Investigation, Writing—Original Draft, Writing—Review & Editing), and Suphi Sen (Formal Analysis, Investigation, Data curation, Writing—Original Draft, Writing—Review & Editing, Visualization).

Conflict of interest: None.

Data availability

Data on costs of fishing were accessed from the Social, Technical, and Economic Committee on Fisheries (STECF; https://stecf.jrc.ec.europa.eu/). The R-code to generate the results will be shared on reasonable request to the corresponding author. Fishmeal and fish oil market data were provided by IFFO by permission.

Appendix A: Deriving marginal forgone oceanic sequestration

In what follows we develop a simple but tractable model of the *marginal forgone oceanic sequestration* (MFOS) of mesopelagic fishing, i.e. the reduction in oceanic carbon sequestration due to an increase in catch of vertically migrating mesopelagic fishes. We demonstrate two ways to do so.

For the first way to derive MFOS we combine Equations (1) and (2) to express the steady-state population as a function of fishing effort (omitting time indices as we are assuming a steady state):

$$rS\left(1-\frac{S}{k}\right)=qSE \Rightarrow S=k-\frac{k}{r}qE \tag{10}$$

Inserting the expression for the catch rate per day-at-sea ($m=qS \Rightarrow q=m/S$) gives

$$S=k-\frac{k}{r}\frac{m}{S}E=k-\frac{k}{S}\frac{m}{r}E \tag{11}$$

Inserting this in Equation (3) (again omitting time indices due to the steady-state assumption) gives the expression for total GHG impact:

$$G=fE+g\frac{k}{S}\frac{m}{r}E \tag{12}$$

Under the assumption that in this emerging fishery catches and hence steady-state harvests are close to the carrying capacity the expression k/S is close enough to 1 to simplify this to

$$G=fE+\frac{g}{r}mE \tag{13}$$

Note that in the second term, mE denotes harvest so that the expression $\frac{g}{r}$ is the marginal impact of that harvest on oceanic carbon sequestration, or MFOS.

The other way to derive MFOS is to define the reduction in biomass as a function of harvest as $D(H)=k-S$. We insert this in Equation (3) and then linearize the expression as follows:

$$G=fE+gD(H)=fE+g\frac{dD}{dH}H \tag{14}$$

We find the expression for $\frac{dD}{dH}$ by solving the steady-state condition of Equation (1) for H, inserting it in the expression for $D(H)$, and taking the first derivative with respect to harvest:

$$D(H)=k-\frac{k}{2}+\frac{k}{2r}\sqrt{r^2-4\frac{r}{k}H} \tag{15}$$

$$\frac{dD}{dH}=\frac{1}{\sqrt{r^2-4r\frac{H}{k}}} \tag{16}$$

Assuming catches are small relative to unexploited biomass, the expression for $\frac{dD}{dH}$ simplifies to $1/r$. Inserting that in Equation (14) gives

$$G=fE+gD(H)=fE+\frac{g}{r}H \tag{17}$$

Note that this is the same expression as Equation (13).

Simplifying climate impact to the expression for MFOS, $\frac{g}{r}$, allows us to analyse the impacts of a 'small' fishery on climate regardless of estimates of current stock size. The

Table B-1. Results of regressing prices of fishmeal and fish oil (logged) on their production (logged).

	ln(Fish meal price)			ln(Fish oil price)		
	(Levels)	(Levels)	(First dif.)	(Levels)	(Levels)	(First dif.)
ln(Production)	−0.090	−0.086	−0.042	−0.270	−0.086	−0.042
	(0.080)	(0.082)	(0.067)	(0.197)	(0.082)	(0.067)
Year	No	Yes	No	No	Yes	No
R^2	0.11	0.15	0.04	0.16	0.15	0.04
Observations	12	12	11	12	12	11

Note: Standard errors are in parentheses. Significance levels are indicated as * $P < 0.10$, ** $P < 0.05$, *** $P < 0.01$.

parameters that we do have to estimate are the amount of carbon sequestered annually per unit of steady-state biomass, or g; and the population's intrinsic annual growth rate, or r. Note, however, that this expression depends crucially on the assumption that the fishery is small compared to the overall stock size. Equation (16) shows that the marginal reduction of steady-state biomass increases with harvest, so as the fishery grows its marginal impact on carbon sequestration will also increase.

Appendix B: Estimating the price elasticity of fish meal and fish oil

In this section, we analyze the association between equilibrium prices and production levels of fish oil and fish meal. By using several specifications, we regress prices on quantities. The results are presented in Table B1. The left and right panels show the results for fish meal and fish oil, respectively. We use three specifications for each product. The first specification uses the levels of the variables in logarithms. The second specification is in first differences of the variables in logarithms. The third specification augments the first one with a year trend. The results indicate that the elasticity of prices with respect to production levels is small. In five out of six estimations, the estimated elasticity is below 0.1. The estimations in first differences indicates an elasticity of 0.04. The estimated parameters are statistically insignificant at conventional levels.

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Handling Editor: Sean Pascoe