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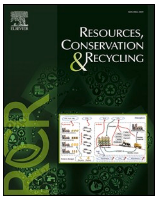

Review

Deep-sea fisheries as resilient bioeconomic systems for food and nutrition security and sustainable development

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ABSTRACT

The frequent deterioration of coastal fisheries has resulted in a need to nourish the world's rapidly expanding population, contributing to a substantial shift toward fishing in the mesopelagic zone. These areas contain a potentially huge amount of fish biomass. Considering that the global population will demand an increase of 60% in food production by 2050, it appears that exploiting the mesopelagic resources is simply a question of time. The present paper reviews the major risks and opportunities related to the exploitation of mesopelagic fisheries. Due to the significance of the uncertainties related to the stock of fish resources, environmental and biodiversity effects of the deep-sea fisheries, this inquiry advocates for the enhancement of sustainable small-sized deep-sea fishery practices on the one hand side and a global moratorium on large-scale mesopelagic fishing on the other hand. Deep seas could provide substantial resources for combating global food insecurity and facilitate a substantial improvement of the nutritional status in the regions plagued by a high incidence of infant mortality and disproportional poverty headcount ratios. For the sake of global and regional food and nutrition security, the exploitation of the biological resources of the mesopelagic zone is a legitimate target, whereby environmental sustainability is the major precondition for the rollout of these kinds of fishing activities.

1. Introduction

The global community is facing an increasing number of concatenated crises with direct implications for the environment, economy, society and politics (Biggs et al., 2011). In addition to the consolidated systemic risk of the economic and financial crises, profound social and ecological vulnerabilities are unfolding and revealing the frailty of food systems (de Raymond et al., 2021; Curran, 2020; Tienhaara, 2010). These vulnerabilities are further exacerbated by the occurrence of public and environmental health shocks and *ecosyndemic* crises such as the COVID-19 pandemic (Gatto et al., 2022; Prieur, 2020; Welsch, 2020; Acharya et al., 2017). Environmental degradation has heavy repercussions on food and nutrition security and risks accelerating the global syndemic of obesity, undernutrition and climate change (Swinburn et al., 2019). The current geopolitical turmoils confirm that resource and commodity sectors are interconnected (Shahzad et al., 2023). The ongoing energy crisis has, indeed, heavily impacted worldwide agriculture and food and nutrition security (Zhou et al., 2023; Bentley et al., 2022; Hellegers, 2022).

These disruptive changes require overpassing risk management and embracing preparedness, mitigation, resilience and adaptation thinking to face upcoming complexity and multifaceted vulnerability (Sikula et al., 2015). In this purview, pursuing robustness, recovery and reorientation, food resilience becomes essential to contrast multilayered

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List of Abbreviations: **BCP**, Biological Carbon Pump; **Edna**, Environmental DNA; **RFMO**, Regional Fisheries Management Organization; **SDGs**, Sustainable Development Goals; **UN**, United Nations; **UNFSA**, Agreement for the Implementation of the Provisions of the UN Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks of 4 December 1995; **VME**, Vulnerable Marine Ecosystems.

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vulnerability, foster sustainable development and empower all stakeholders (Zurek et al., 2022).

Environmental sustainability is noteworthy endangered by these threats and calls for holistic outlooks (Cantone, 2021; Gatto, 2020). Ecological challenges arise from anthropogenic interventions in biophysical processes, which impact climate change and cause the loss of biodiversity (Gatto, 2022). Due to the increase in climate shocks, conflicts, human population and pandemics the global nutrition system is unstable and urgent actions are necessary to secure efficient and sustainable resource management (St.John et al., 2016, p.1).

Especially during the pandemic and economic slowdowns the problems of hunger, malnutrition and food insecurity have dramatically worsened (UN, 2021). In 2019, almost 690 million people in the world were undernourished. Currently, over 821 million are suffering hunger and starvation mainly due to economic downturns and climate change, up by approximately 131 million from 2019 and nearly 191 million from 2014 (UN, 2021). It is indicated that the growth of these sufferers already started before COVID-19 and even after the pandemic this trend may continue. The estimation of the global population will rise by 2050 from about 7 to 9.2 billion and will require an increase in global food production of 60% (Agovino et al., 2018; FAO, 2021).

In this framework, meeting sustainable development goals (SDGs) is key (UN, 2015). To achieve the SDG's second goal, 'Zero hunger by 2030′, further steps need to be taken as soon as possible. The cruciality of fisheries and aquaculture for tackling food security, nutrition and improved livelihoods is being advocated by international development agencies and has consolidated notorious fame (Béné et al., 2016). On top of that, the contribution of water in providing a large amount of food to the world's population – and above all the poor and the vulnerable – is a consolidated item (Kent, 1997). Oceans and waters can also highly contribute to ecosystem services, including the provisioning of aquatic food security, human and ecosystem health and food diversification (Bidoglio and Brander, 2016; Jennings et al., 2016). In this vein, fishing and aquaculture are envisaged as increasingly dominant assets for reaching sustainable development in the near and remote future (Tacon et al., 2022; Stankus, 2021; Blanchard et al., 2017).

To formulate a solution, this work investigates the most underexplored territory of our earth – the deep oceans – which bears a huge potential for new resources to secure food and nutrition (Campanya-Llovet et al., 2017). In this context, land-based food does not contain essential micronutrients and fatty acids as ocean-based nourishment, which is crucial in contributing to global food and nutrition security (Costello et al., 2020, p. 95).

The deep sea is defined as the area comprising the waters and seabed below a depth of 200 m, corresponding to 64% of the surface of the earth and 95% of our planet's ocean area (Danovaro et al., 2020, p. 181; UNEP, 2007, p. 9). Fisheries have changed the allocation of fish and now take place in the deep oceans. While growing populations and rising affluence have increased global demand for fish, the increasing abundance of fish from epipelagic oceans has pushed industrial fisheries further away from home ports and markets (Norse et al., 2011, p. 308). This review paper will highlight the mesopelagic zone function, asking whether the deep-sea fishery can be sustainable and able to foster food and nutrition security, carrying improved livelihoods all around the world – and, above all, empowering vulnerable people in developing countries.

The ocean contains unique biodiversity, provides food resources and is a major sink for anthropogenic carbon. Marine protected areas (MPAs) are an effective tool for restoring ocean biodiversity and ecosystem services, but currently, only 2.7% of the ocean is highly protected (Sala, 2021, p. 397). Nonetheless, there is a tension between marine protection and ending poverty, since declines in fisheries are risky regarding the labor market and food security, especially in developing countries (Hoegh-Guldberg et al., 2019, p. 85). In fact, it is conceivable to expect the reduction of improving efficient fish catch and shifting diets from terrestrial animal-based foods to ocean-based proteins can tangibly help to reduce malnutrition and invert food purchasing and nutrition habits, curbing the modern plagues of undernutrition and overnutrition (Sundin et al., 2021; Hoegh-Guldberg et al., 2019, p. 63).

To make diet shifting feasible, one source of fishing could be the deep sea, as there is evidence that its biomass is greater than previously assumed (Govindarajan et al., 2021). Research has shown that deep-sea fishes are mostly safe for human consumption and a good source of minerals. Previous inquiries also suggest that individuals with a dietary pattern that included omega-3-rich deep-sea fish had a reduced prevalence of fragility (Ajeeshkumar, 2021; Lo et al., 2017).

The mesopelagic (200–1000 m) makes up approximately 20% of the global ocean volume and plays a significant role in biological carbon pumps (Davidson et al., 2013). The mesopelagic zone holds a potentially huge stock of fish resources (Irigoien et al., 2014; John et al., 2016; Webb et al., 2010). It is, however, hidden from satellite observation and a lack of globally consistent data corresponds with substantial uncertainties with regard to the ecological and biodiversity repercussions of the extraction of the biological resources of the mesopelagic zone. However, acoustic deep scattering layers are prominent features of the mesopelagic zone. These are vertically narrow (tens to hundreds of meters) but horizontally extensive layers encompass fish and plankton resources and are easily detectable by means of echo sounders (Proud et al., 2017).

This review aims to deepen our knowledge of sustainable management of mesopelagic areas for enhanced food and nutrition security. To the best of our knowledge, this is the first attempt to produce a similar exercise, indicating the novelty of this survey. The paper is organized in the following way. addresses the ambivalence of the exploitation of the biological resources of the mesopelagic zone. sums up the performed methods. delves into the mesopelagic zone an the risks incurred by those explorations. depicts recent advances in topical international trends and management. Section 6 concludes.

2. Sustainable development and the deep seas

Life below water has been assigned as an entire sustainable development goal – SDG 14 – and ten specific targets including avoidance of marine pollution, ecosystems protection, sustainable fishing, hamper overfishing and implementing and enforcing international sea law (UN, 2015). The most relevant piece of Global Goals from the Agenda 2030 for this inquiry is Target 14.4. It foresees "By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics ". The only indicator – 14.4.1 – measures "the proportion of fish stocks within biologically sustainable levels".

Sustainable management of fisheries is compelling to achieve sustainable development objectives. Business performance and marketing strategies can dramatically change the socioeconomic and ecological results of sea resources and food from the oceans (Risitano et al., 2021). As a business sector, fishery management displays elevated sensitivity to the territory and societal and environmental issues, whereas a wide spectrum of stakeholders is involved in the decision-making process (Scarpato et al., 2020).

The potential of food coming from seas, lakes, rivers, oceans and other waters is often overlooked and can provide highly nutritional outputs, hence fundamental to reaching diverse sustainability scopes (Ferreira et al., 2016). However, resource governance often carries unsustainable management practices (Van Hoof et al., 2019; Costanza, 1999). A management framework for sustainable ocean uses is imperative due to the high risks caused by large-scale exploitation and fleets management (Kourantidou and Jin, 2022). In this context, the mesopelagic and epipelagic fishery is absorbing increasing attention and is likely to grow with new explorations of the mostly-unknown mesopelagic zone. Nevertheless, deep-sea ecosystems and resource protection seldom undergo standardized or planned management practices, causing high risks to the sustainability of the sector (Paoletti et al., 2021). This urgency calls for prompt and tailored regulation, policy and governance.

Forecasts predicted that most of the deep seas are anticipated to experience global warming by 2041–2060 and 2081–2100 (FAO, 2018, p. xix-xxi). At depths of 200–2500m, where deep-sea fishing takes place, rising temperatures and falling oxygen levels have previously been observed. Acidification, seabed warming, deoxygenation and a reduction in particulate organic matter flow to the bottom are predicted to exceed natural variability in several areas during the next 20–50 years (FAO, 2018, p. 158). Bathyal depths in the Northwest Atlantic, the Barents and western Greenland Seas, the Red Sea and the Sea of Okhotsk are expected to be significantly affected. If long-term environmental changes surpass the capacity of marine species to adapt, their populations' long-term viability may be threatened (FAO, 2018, p. xix-xxi).

As seen in the East Mediterranean Transient, a single event could cause sudden changes in deep-water biomass characteristics, with substantial consequences for deep-sea ecosystem processes (FAO, 2018, pp. 11–12). Indeed, fishing changes the structure of an ecosystem and can lead to global extinction by making species abundant (Hilborn et al., 2015, p. 1434). In the late 1980s, several fish stocks around the world collapsed as fisheries' resources were unable to withstand the rapid increase in fishing efforts, so new approaches to fisheries management (fish stocks, environment, etc.) have been demanded since then (FAO, 2020, p. 92).

The decreasing catch rate, which is due to a general lack of efficient management in most regions of the world, is a signal of a lack of sustainability in fisheries and this problem is not solved by breeding carnivorous species (Zeller and Pauly, 2019, p. 4). For a world that relies on the ecosystem services provided by the oceans, it is important to know how sustainable deep-sea fisheries can be (Norse et al., 2012, p. 307) since the sustainability of seafood production mainly depends on the system of fishery management to adjust appropriate conditions (Hilborn et al., 2015, p. 1433). Additionally, fragile deep-water ecosystems can be threatened by deep-sea fisheries. It is proven that many deep-sea fish stocks are being exploited beyond sustainable standards, which emphasises the need to enhance the management of the species (Villasante et al., 2012, p. 32).

3. Methods

The inquiry at hand has the purpose to investigate the sustainability of deep-sea fisheries for granting improved food and nutrition security, resilience and livelihoods. To this end, a literature review is performed on specific subjects and searches. Both scholarly and gray literature were annexed. To date, no publication inspected these subjects, showing a literature gap. Therefore, this survey has the advantage of offering a topical contribution to this stream of research.

Scientific publications were selected from international peer-reviewed journals in the field of sustainable development as well as environmental, food and marine policy and management gray literature resulted from inter-governmental and non-governmental organizations' reports in the field of food and environmental security and sustainability.

The present study juxtaposes the risks and opportunities of the mesopelagic fishery. To this end, the inquiry pursues the following methodological approach. We reviewed three strands of literature in the fields of environmental, food, biological and marine research, focusing on deep-sea management. We highlighted the corpus of literature that has not been efficiently compared from past scholarship till now. The criteria for including a publication within this review was to pertain to one of the selected strands of literature.

The first line of literature is related to selected climatic and environmental aspects of deep-sea fisheries. The second strand is about the role of deep-sea fisheries as related to the role of food availability and security. The third cluster concerns biodiversity aspects. Based on these publications, the study attempts to juxtapose and assess the potential risks and opportunities sorting from deep-sea fisheries and recommends gradual exploration of deep-sea fisheries based on empirical evidence. The work lastly supports the use of moratorium instruments because of grave environmental risks. All the explorations and exploitations of deep-sea fisheries should, indeed, be run by independent auditing, which would account for environmental risk. The methodological rationale is summed up in a diagram – Fig. 1.

4. The mesopelagic zone

The entire ocean column, the pelagic zone, is divided into different areas, including the epipelagic and mesopelagic space (FAO, 2021) (Fig. 2). While the epipelagic zone is defined as the first 200 m of the water column, receives sunlight and is seasonally influenced by temperature and salinity (MBNMS, 2019), the deep sea ($>$ 200 m depth), which constitutes 95% of the world's ocean volume, is the least explored biome on earth (Danovaro et al., 2020, p. 181). It includes the mesopelagic zone (twilight zone) which spreads out over a depth of 200–1000 m below the surface of the ocean (FAO, 2021) and represents about 20% of the global ocean volume (Proud et al., 2017, p. 113), as very little light reaches this area, food is becoming less available. Hence, during dusk most of the deep-sea animals move towards the water surface for food, trusting the darkness to protect them from enemies. In the early hours, they sink back down to the mesopelagic zone, where they can protect themselves. Sutton et al. (2017) created a global biogeographic classification of the mesopelagic areas that include 33 ecoregions (Fig. 3).

Due to the daily migration of mesopelagic fish through the zones, this vast mesopelagic area is a critical part of the global carbon cycle and wider marine food webs (Wright et al., 2020, p. 1). Due to this migration, energy is transferred from the surface to the deep sea (Wright et al., 2020, p. 6). It is estimated that the earth's oceans are a reservoir for 31% of anthropogenic CO_2. Per year, 100 Gt of organic carbon is absorbed by the ocean surface waters, thereby up to 10 Gt of it is shifted to the mesopelagic zone (McKenzie et al., 2020, p. 2). The consequences of overexploitation are potentially severe as mesopelagic fish are essential components of the biological carbon pump (BCP) (Giering et al., 2014, p. 480; Govindarajan et al., 2021, p. 2).

4.1. Biodiversity

It is commonly accepted that marine biodiversity contributes to the ecosystem's sustainability and efficiency by enhancing its resistance to environmental change (Bosch et al., 2010, p. 114). In comparison to epipelagic, benthic and coastal fish species, mesopelagic fish is relatively unknown. This is largely due to the region's lack of access to information, due to the high costs. Oceanographic vessels and cutting-edge technology capable of sampling at vast depths are required (Caiger et al., 2021, p.766). In this context, one of the major challenges in deep-sea ecology is measuring biodiversity and linking it to flux performance (Costa et al., 2020, p. 2).

Recent estimates indicate that on earth, fishes in the mesopelagic zone are the most abundant vertebrates, with larger estimated biomass than previously assumed, ranging from 2 to 19,5 Gt (Hidalgo and Browman, 2019, p. 609; Caiger et al., 2021, p. 765). The biomass results before 1980 (approx. 1 Gt biomass) appear to be underestimated because sampling devices cannot quantitatively sample mesopelagic fish. Since fishes appear to have an avoidance behavior from a pelagic trawl, the acoustic abundance estimates are always higher than the net-based estimations (Kaartvedt, 2012, pp. 1–4).

Since the twilight zone still receives enough light to allow adapted animals the visual predation (Christiansen et al., 2021, p. 1), some species do not have to migrate to the upper zone (Ariza et al., 2016, p.

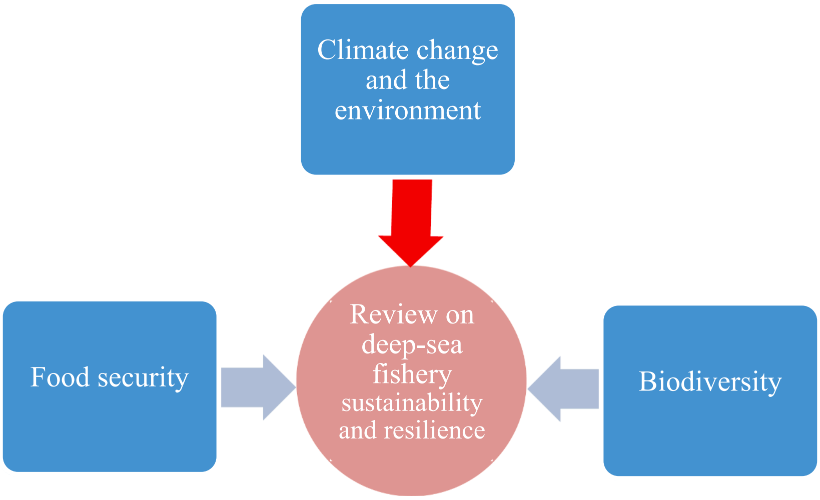

Fig. 1. Review rationale (Authors' own illustration).

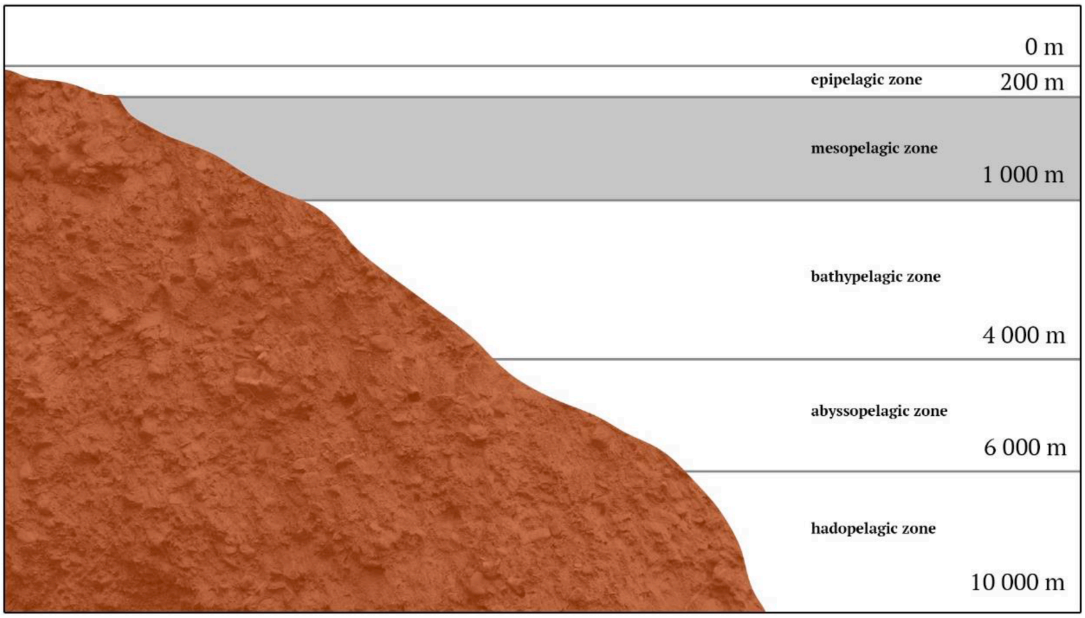

Fig. 2. Open-ocean depth zone schema used to define mesopelagic species (Authors' own illustration).

90) (Fig. 4). The main group of the mesopelagic zone are micronekton between the range of 2 and 10 cm, consisting of crustaceans (adult euphausiids, mysids and pelagic decapods), fishes (mesopelagic species and juveniles of pelagic nekton species) and cephalopods (small species and juveniles of large oceanic species) (Brodeur et al., 2005, p. 7). During the day, most of the mesopelagic biomass (e.g. zooplankton, jellyfish, squid and fish) live in the deep scattering layers (DSLs) (Fig. 4) (Brodeur et al., 2005, p.7; Proud et al., 2019, p. 718).

The daily vertical migration from the epipelagic to the mesopelagic zone of micronekton contributes to the rapid vertical transport of organic materials. It is described as the BCP, transporting carbon as well as anthropogenic materials into deep-sea ecosystems. In the near-surface water, these micro nektonic organisms can in turn be eaten by epipelagic predators (large nekton species that migrate with the micronekton such as tuna, sharks and swordfish) (Brodeur et al., 2005, p.7).

A change in the size of dominant plankton cells, jellyfish or salp blooms can have a profound influence on the transport of fresh organic matter to great depths (Smith et al., 2014). The ecosystem and its productivity depend on the amount and rate of biogeochemical cycling – e.g. the exchange of carbon as an energy flux among species within a community (Smith et al., 2009, p. 19,216). The growth and life span of mesopelagic fishes vary depending on the species (Fig. 5), but in comparison to many coastal and deep-sea benthic species, they are short-lived (Caiger et al., 2021, p. 769). Reported fecundity values of mesopelagic fishes are generally low compared to epipelagic species.

Since the number of an individual's offspring is related to energy availability, it is possible that the low environmental productivity and vertical migration may limit the reproductive potential of mesopelagic fishes. Nevertheless, estimates suggest that some mesopelagic fishes, like the Myctophid D. Suborbitalis, may be comparable to shallow-water species in terms of annual or lifetime reproductive output (Caiger et al., 2021, p. 774).

The routes of dispersal are mostly unknown and the species have larger possible ranges in deep waters than in shallow waters and benthic environments (Costello and Chaudhary, 2017, p. 520). Morato et al. (2006, pp. 31–32) have illustrated that between 1950–2000, landings of fish species have shifted globally from shallow to deeper water species. One probable negative effect of this is the increase in the average

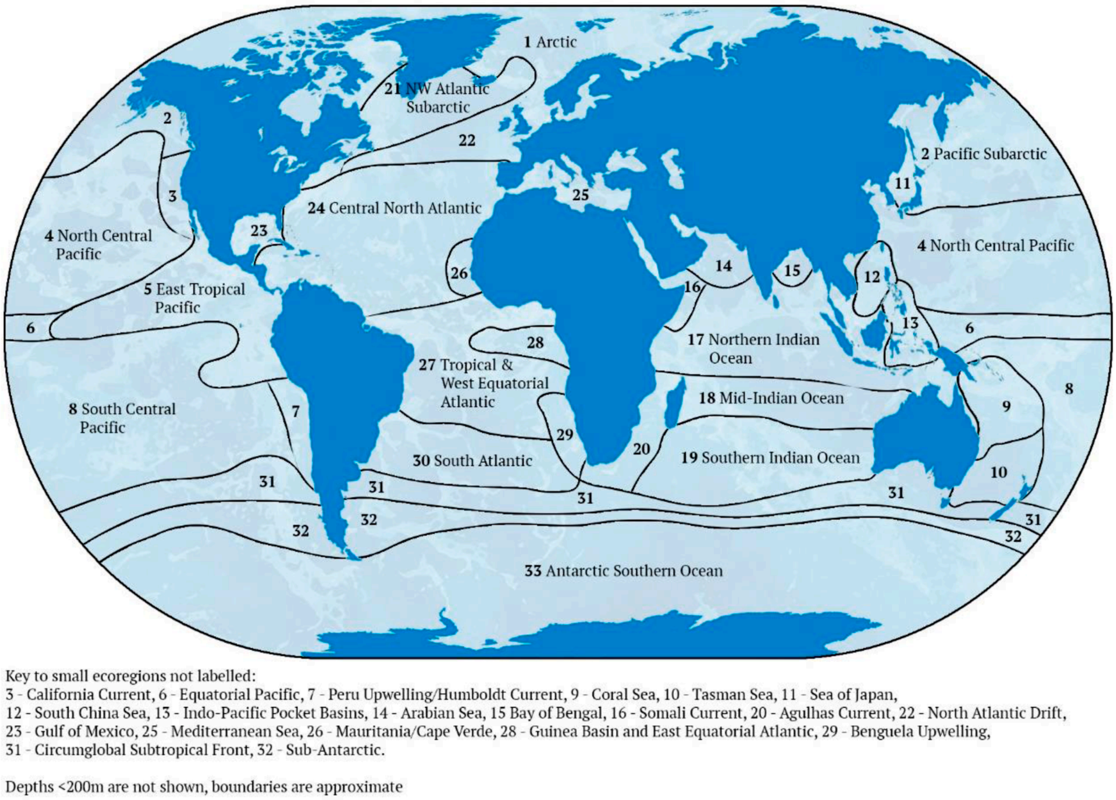

Fig. 3. The mesopelagic ecoregions of the world oceans (Authors' own illustration, adopted from Priede, 2017, p. 320).

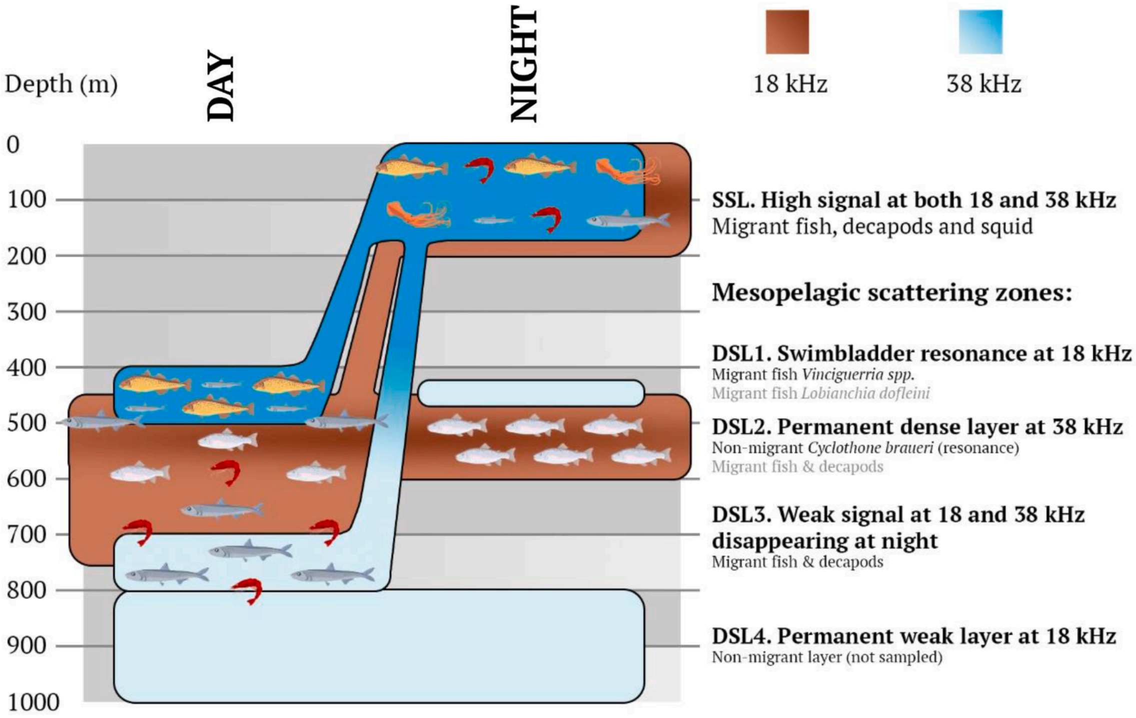

Fig. 4. Distribution of shallow and deep scattering layers (SSL and DSLs) based on observations at 18 and 38 kHz in waters around the Canary Islands (Authors' own illustration, adopted from Ariza et al., 2016, p. 89).

lifespan of the fish species caught, since species with longer life spans, larger body size, slower growth and consequently later sexual maturity are more sensitive to overfishing and extinction. Climate change and other factors make this difficult to forecast but there are certain threshold values (e.g. for temperature, oxygen, or pH) that, if surpassed, can result in fast change (over 2–10 years) – e.g. distributional changes

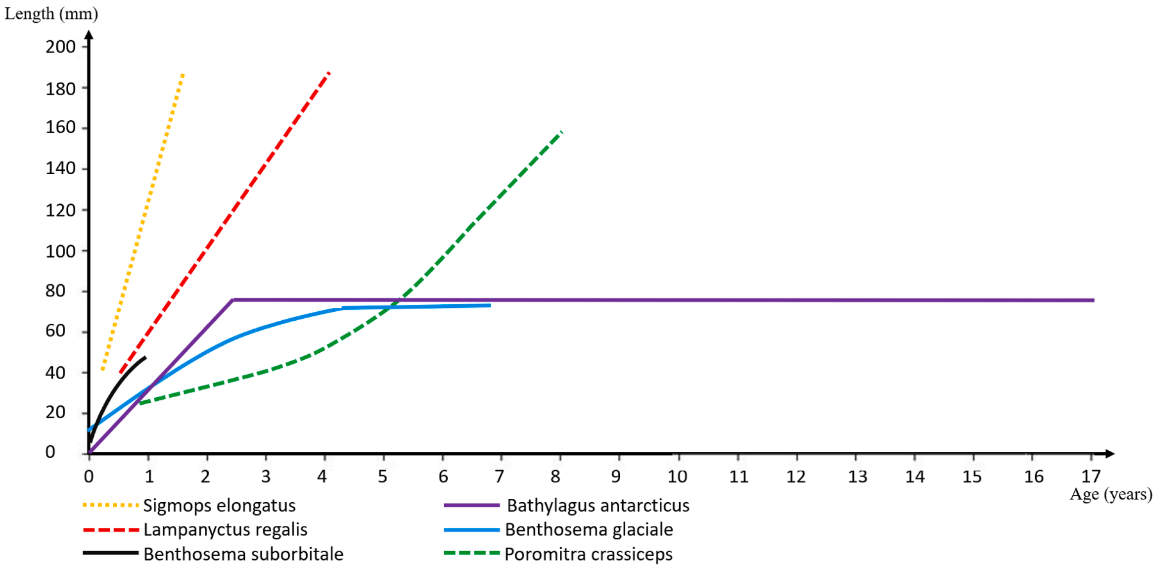

Fig. 5. Example growth curves for mesopelagic fishes (Authors' own illustration, adopted from Caiger et al., 2020; and Liu et al., 2022).

in fish stocks, which will lead to major transformations in the location of fisheries.

Taxa that lack the ability to colonize newly suitable areas will not be redistributed, resulting in local extinctions in fish populations (FAO, 2018, p. 158). The vulnerability and risk of climate impact were evaluated for 41 deep-sea fishes, with the results indicating that all species are expected to face significant levels of climate hazards, with the risk of effects by 2100 being on average 13% higher than the risk by 2050.

Because of their bigger body size and limited heat tolerance, Antarctic Toothfish, Yellowtail Flounder and Golden Redfish were the most vulnerable. The Argentine Shortfin Squid, as well as the Argentine and Blackbelly Rosefish, are among the least threatened species, whereas the most vulnerable species are found in the Northern Atlantic Ocean, Indo-Pacific region, West-African Coast and the South-Pacific (FAO, 2018, p. xxii). Furthermore, mesopelagic species are a potential source of fishmeal and nutraceuticals, which is why fisheries have lately turned their attention to the mesopelagic zone (Kourantidou and Jin, 2022).

Sustainable management is difficult because of the lack of knowledge about their life history, distribution and ecology (Govindarajan et al., 2021; Hidalgo and Browman, 2019, p. 5). All these factors have an impact on climatic consequences due to the role of the deep-sea fishes as a BCP (Govindarajan et al., 2021, p.1f), creating a devastating spiral (Fig. 6). The loss of species impacts the overall function of the ecosystem, thus creating a feedback loop that alters species biomass productivity and high biodiversity increases the resilience of ecosystems to disturbance (Pfisterer and Schmid, 2002). Consequently, maintaining biodiversity is an important goal in the pursuit of sustainable resource utilization (Kachelriess et al., 2014, pp. 169ff.). Thus, before irreparable anthropogenically induced changes appear, improving the understanding of the composition, abundance and distribution of the mesopelagic fauna is an urgent need (Govindarajan et al., 2021, pp. 1–2).

4.2. Sustainability of fishery methods

Fishing is one of the most energy-intensive food production systems in the world, relying mostly on fossil fuels and emitting greenhouse gasses (GHG) (Wilson, 1999, p. 46). Already in 2016, Greer et al. (2019) stated that CO_2 emissions from global fisheries (in both absolute terms and in terms of emissions intensity) are significantly higher than previously thought. Since 1950, ocean fisheries have emitted a minimum of

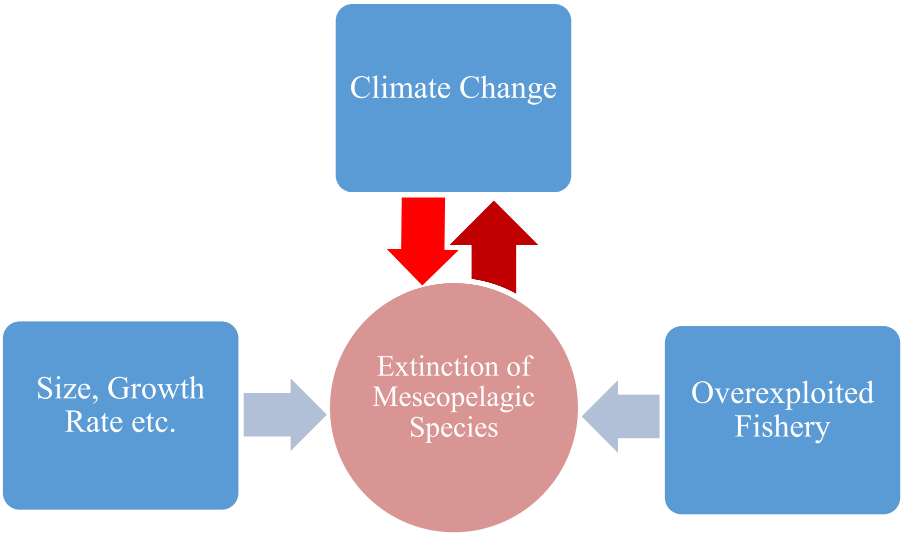

Fig. 6. The extinction of mesopelagic species and its external impacts (Authors' own illustration).

0.73 billion tonnes of CO_2 (GtCO_2). Furthermore, tuna and other large pelagic fishes, which feed the mesopelagic, are already heavily or completely overexploited, putting the structure of marine food webs at risk (Zeller and Pauly, 2019, p. 4).

Large marine fish carcasses sink and store carbon in the deep sea but fisheries have taken a significant quantity of this “blue carbon”, causing increasing CO_2 emissions in the atmosphere. 43.5% of the blue carbon extracted by the world’s ocean fisheries comes from areas, which would be unproductive without government subsidies. CO_2 emissions would be decreased if a restriction on blue carbon extraction by fisheries was implemented (particularly in unprofitable locations) since less fuel would be consumed and a natural carbon pump would be reactivated by recovering fish stocks and boosting carcass decomposition (Mariani et al., 2020, p. 1). Nevertheless, in case of a restriction, the social goals of fisheries management and policy need to be considered, since they tend to favor small-scale fisheries and generate jobs (Greer et al., 2019, p.7).

Regarding sustainable fishing, selective fishing is requested, whereby the fishermen only catch the marine animals they want to capture (Greenpeace, 2020). Depending on the behavior of the species, different methods are used in fishing for shallow-water and deep-sea species (Priede, 2017, p. 364).

4.2.1. *Fishery fleets and fuel*

Some deep-sea fishing vessels fish on the high seas, while others are within exclusive economic zones. The majority of vessels target several species and change gear regularly (FAO, 2021). Due to fuel subsidies, some nations are able to deploy large distant-water fishing fleets which poses a danger to developing countries’ resource bases. Many distant-water fleets are unable to operate profitably without fuel and other harmful subsidies. Social justice, environmental and economic sustainability are incompatible with the excessive subsidization of industrial fisheries (Greer et al., 2019, p. 7; Zeller and Pauly, 2019).

Zeller and Pauly (2019, p. 4) stated that in comparison to small-scale fishing, industrial fishing employs fewer people and uses more fuel for every ton of fish landed. The sector produces around 10 million tonnes of waste every year and 1/3 of the land fish are utilized as animal feed (Table 1). If two small-scale fisheries would replace an industry, employment could be created radically, fish caught for human consumption could increase about 21 million tonnes (surplus of no waste) and CO_2 emissions could be decreased to 4–10 tonnes per ton of fish (Table 1). Rather than growing fisheries further, most industrial fisheries should be stopped and developing maritime nations – e.g, African countries – could be encouraged to create their own domestically owned and managed fisheries. This would eventually produce positive effects on food security and impact the contrast to nutrition vulnerability jeopardy – especially in developing countries (Loring et al., 2019; Bell et al., 2018; Teh and Pauly, 2018; Bené et al., 2007).

Before developing or implementing strategies to reduce CO_2 emissions, it is important to understand local fleet dynamics (Greer et al., 2019, p. 7). Greer et al. (2019, p. 7) demonstrate that, if a fleet of ten 12-meter vessels were replaced with a single 35-meter vessel, emission intensity and overall fleet CO_2 emissions would stay equal. If the sector is dominated by small-scale fishermen, a program to introduce diesel engines may be appropriate to reduce emissions (Greer et al., 2019, p. 7). The frequent unsustainability and ecological footprint of the large-scale fishery is a multifaceted global problem. The issue is apparently counterintuitive and can arise despite local industry greenness and good CSR practices (Kourantidou and Jin, 2022; Gatto and Busato, 2020).

Table 1
Contrasting large-scale (i.e., industrial) and small-scale (Adapted from Zeller and Pauly, 2019, p. 5).

Fisheries Benefits	Large-scale fisheries	Small-scale fisheries
Annual catch	ca. 45 million tonnes	ca. 28 million tonnes
Fish and other sealife discarded at sea	10 million tonnes	none
Annual catch reduced to meals and oils	30-35 million tonnes	about none
Fuel consumption per ton of fish	5-20 tonnes	2-5 tonnes
Number of fishers employed	about ½ million	About 12 million
Government subsidies	25-30 billion USD	5-7 billion USD

Additionally, the transition from gasoline/diesel to electric motors, as well as a viable alternative for on-board food preservation – such as waste-heat powered refrigeration technologies – should be promoted (Greer et al., 2019, p. 7, Palomba et al., 2017). In terms of controls are necessary. Amongst the alters and monitoring tools to be possibly adopted, deep learning-based techniques for improving real-time vessel carbon dioxide emission control and predicting real-time vessel carbon dioxide emissions could be implemented (Wang et al., 2021).

4.2.2. *Static nets*

In the Northeast Atlantic, gillnets (Fig. 7), entangling nets or bottom set trammel nets have been used to catch hake (100–600 m depth), anglerfish (100–800 m depth) and deepwater sharks (800–1600 m depth). Multiple net fleets, with a total length of up to 100 km per trip, can be deployed by each vessel. It is a flexible and fuel-efficient fishing method, but fish are often injured during capture, so catches are usually of lower quality than with traps and longlines (Priede, 2017, p 364). Gillnets can be labor-intensive as fishermen must manually release the catch from the net.

Because bottom trawling displaces or destroys the nets, abandoned gillnets are common in regions where bottom trawling is often used (Suuronen et al., 2012, p. 143). Even if this method is highly effective and depends on the mesh, to some degree size-selective, it has been recorded that up to 15 non-target species have been caught by this method. As a result, deep-sea gillnetting is categorized as a potentially devastating fishing technique, which is why measures are being taken in some countries to restrict or ban this practice (Priede, 2017, p. 364).

4.2.3. *Bottom trawling*

Bottom trawling dominates deep-sea fisheries (Fig. 8), accounting for almost 80% of total deep-sea capture in 2001 (Gianni, 2004, p. 34). Prawns, Orange Roughy, Redfish, Oreos, Alfonsinos and Grenadiers are the major target species (Pauly et al., 2003, p.1360). In the North Atlantic, where vessels commonly target a range of fish species, most deep-sea fishermen are bottom trawlers (FAO, 2021).

In bottom trawling the main technique used is the classic otter trawl, which is towed along the seabed and has a great impact on marine ecosystems, which include seafood stock impoverishment, benthos mortality and sediment resuspension. In this way, organic carbon extracted daily by trawling in the area under investigation is expected to account for 60–100% of the input flux (Priede, 2017, p. 365; Pusceddu et al., 2014, p. 8861). Such an impact will cause the degradation of deep-sea sedimentary habitats and an infaunal depletion without providing a positive economic return (Esteban Aniol, 2013, p.1).

Increased trawling-induced sediment erosion is also linked to decreased fauna biodiversity and modifications in the biological characteristics of benthic aggregations. Especially compared to untrawled regions, trawling operations have reduced nematode biodiversity in trawled sediments by around 25%, which also results in a significant reduction in organic carbon turnover rates (Pusceddu et al, 2014, p. 8863). Pusceddu et al. (2014, p. 8852–8864) discovered that trawled sediments in deep-sea zones have a reduced organic carbon turnover and are substantially decreased in organic matter content, biodiversity and individual biomass, compared to untrawled regions.

According to research by Witte et al. (2003) and Mayor et al. (2012), trawled sediments are commonly accompanied by a decline in the fraction of organic matter of algal origin, which is the tiny amount of biomass that is most nutritional to heterotrophic consumption and thus represents the most essential food source of the deep-sea benthic fauna.

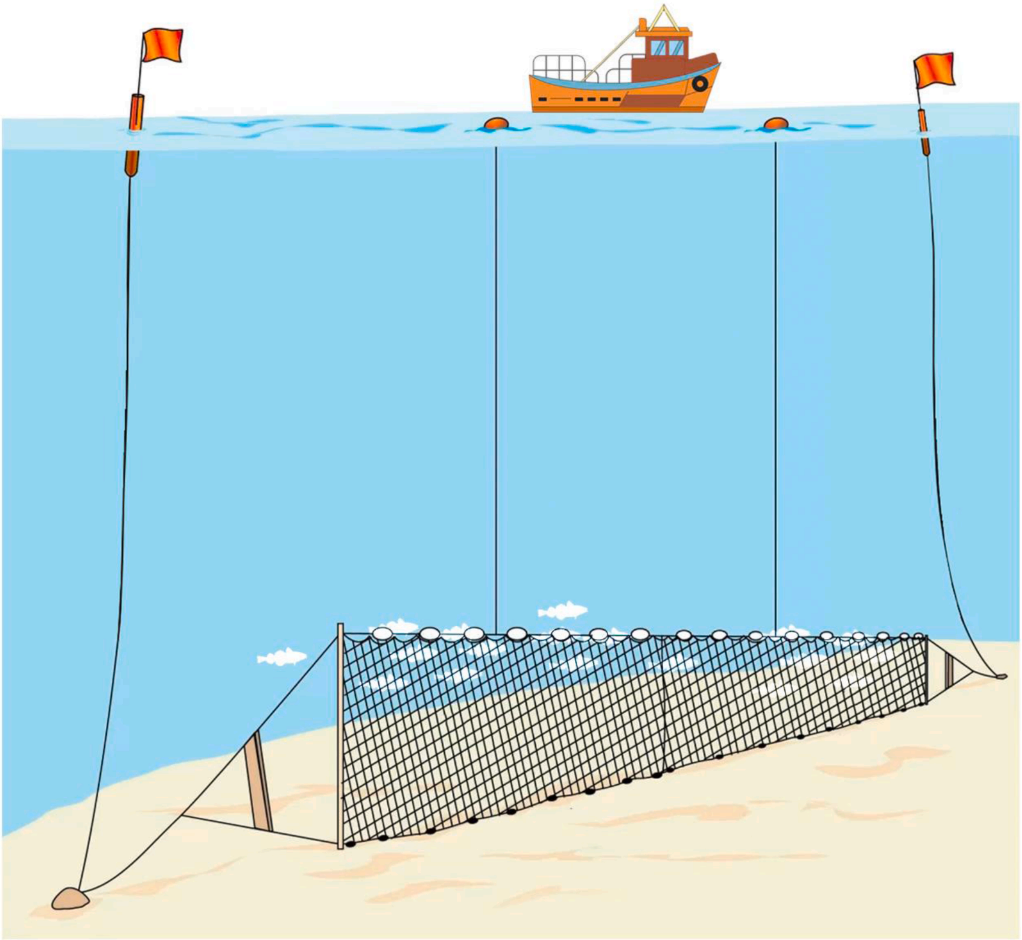

Fig. 7. Bottom-Set Gillnet (Authors' own illustration).

As a result, the constant trawling-induced discharge of higher proportions of high-quality nutritional resources in this deep-sea ecosystem, along with a reduction in organic carbon cycling, suggests that bottom trawling might worsen the inherent food constraint of the deep-sea sediments (Pusceddu et al., 2014, p. 8863).

4.2.4. *Baited lines, traps and pots*

One of the oldest methods used by man is to attract fish with baits. It is used extensively by long-liners, who can set thousands of hooks simultaneously in the water column or on the seafloor (Fig. 9). For most rays, sharks and many gadiform fish this method is very effective. According to studies, bottom trawling can be substituted by baited lines and traps, which reduces seafloor pressure, using less bycatch per landed kilogram and fuel consumption is relatively low, depending on the distance of vessels to fishing grounds – e.g., inshore fishing with hook and line compared to offshore fishing with longlines – (Loughman et al., 2013, p. 809; Suuronen et al., 2012, p. 142; Hammarlund et al., 2021, p. 94; Hornborg et al., 2016, p.142).

Even though this method catches high-quality fish and the production costs of the lines are relatively low, it is labor-intensive. Additionally, since the bait resources are offered for food, the cost of bait is mostly high (Suuronen et al., 2012, p. 142). Moreover, it was estimated that 28% of all lines and 8.5% of all traps were lost in the ocean in 2017 and also have the potential to harm seabirds, sea turtles and sharks – which are often protected or endangered species (Richardson et al., 2019, p. 12; Suuronen et al., 2012, p. 142). Furthermore, it was found that in the Northeast Atlantic, only 20% of the deep-water fish species caught by bottom trawls were attracted to baited traps. The Roundnose Grenadier and Orange Roughy or other commercially important deep-sea species are not attracted by bait (Priede, 2017, p. 364). Therefore, the question arises whether this method is effective enough for deep-sea fisheries.

5. International trends and management

The deterioration of many coastal fisheries has resulted in a need to nourish the world's rapidly expanding population, contributing to a substantial shift toward fishing in the mesopelagic zone (Caiger et al., 2021). Current biomass estimates are highly imprecise (Proud et al., 2019, p. 13) and over-harvesting was caused when industrial fleets target regions outside of national authority (Cullis-Suzuki and Pauly, 2010, p. 1036; FAO, 2014).

Since the late 1980s, the long-term trend in total global capture fish production has been comparatively stable, but it reached its peak of 96.4 million tonnes in 2018 (Table 2). Similarly, inland water captures peaked at 12 million tonnes in 2018, about twice as high as the median between 1986 and 1995 and total world fish production was predicted to be 178.5 million tons (FAO, 2020, pp. 2–6). Thus, the total global fish production and aquaculture in 2018 (0.1785 Gt) would account for approximately 0,009% to 0.09% of the predicted mesopelagic biomass (2 - 19,5 Gt).

One of the few high-biomass fish species that have not yet been exploited is the mesopelagic stocks – especially the lanternfish. Nevertheless, considering that the global population will demand an increase of 60% in food production by 2050, it appears that exploiting the mesopelagic resources is simply a question of time (Hidalgo and Browman, 2019, p. 613). Assuming that the total demand for fish capture in 2050 will be 60% higher than in 2018 (154.2 million tonnes), then the

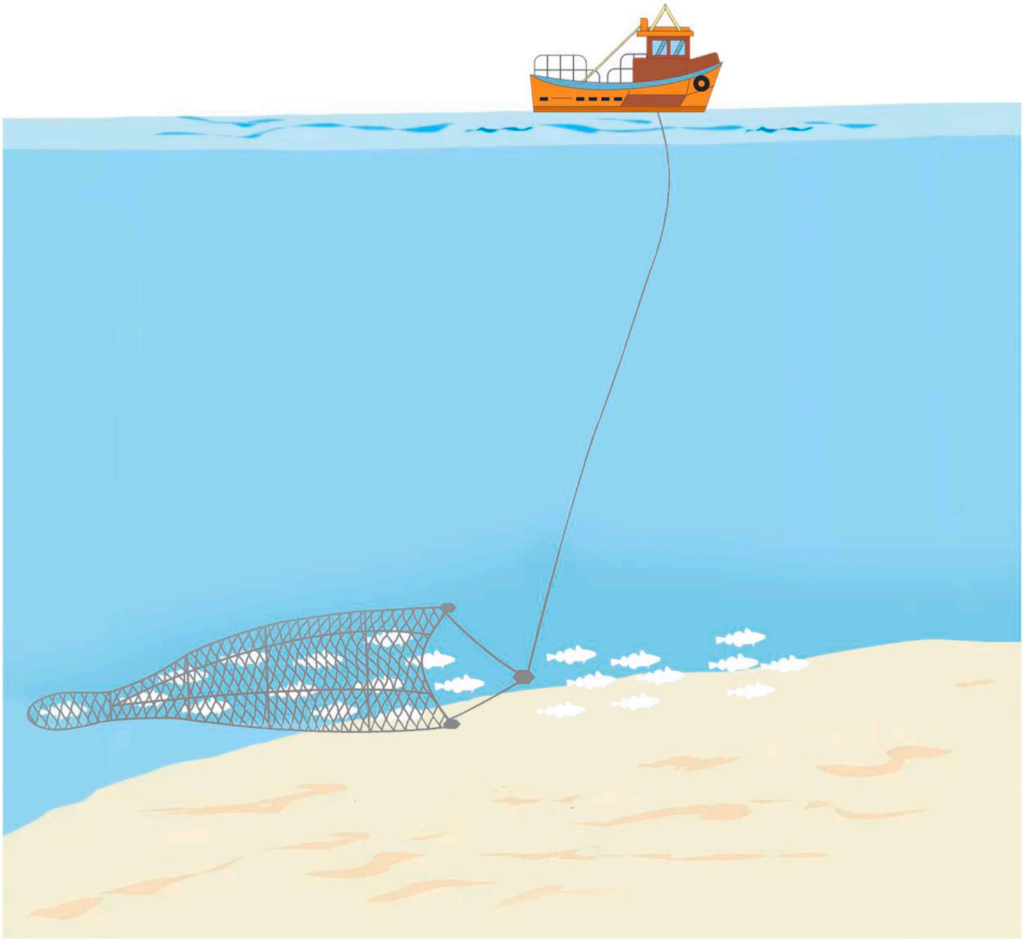

Fig. 8. Bottom Trawling (Authors' own illustration).

total demand in 2050 would be 57.8 million tonnes higher. Extracting this required 0,0578 Gt of surplus from the mesopelagic zone would correspond to 0.003–0.03% of its estimated biomass (under the condition that the estimated biomass remains at 2 - 19,5 Gt).

In the case of a demand surplus and even if the current total fish production is moved to the mesopelagic fishery, these extractions do not really appear to be large. Thus, as long as the factors contributing to the extinction of mesopelagic species are kept in mind, there is a chance that shifting the fishery from epipelagic to the mesopelagic zone could provide jobs, food and help to regenerate the epipelagic fishes. However, a survey by Prellezo (2019) has demonstrated that mesopelagic fisheries are not a viable alternative to existing commercial fisheries in the Bay of Biscay, due to lower lending profitability. For the fleet they examined, a new commercial mesopelagic fishery is only viable, if demand and therefore the price of mesopelagic goods, grows (Prellezo, 2019, p. 778).

Apart from this, deep-sea research in industrialized countries is still associated with high investments (Costa et al., 2020, p.8). While basic information on deep-sea ecosystems in terms of biodiversity (species richness and biomass) is gradually being collected, there are still gaps in our knowledge of how the interaction between geo- and bioprocesses affects ecosystem functioning (Costa et al., 2020, p.13). One of the major challenges in determining the function of mesopelagic biodiversity in the BCP and their effect on climate regulation in the next decades is quantifying carbon fluxes from primary production to mesopelagic fish and several other organisms (St. John et al., 2016, p. 4).

The lack of understanding disrupts the implementation of international agreements such as the UN Resolution 61/1054 to conserve 'Vulnerable Marine Ecosystems', or the Aichi targets, which are related to the sustainable management of marine exploitation (St. John et al., 2016, p. 4). In the coming years, research on deep-sea biodiversity worldwide will increasingly focus on quantifying the services provided by ecosystems, relating to biotic (such as deep-sea fisheries) and abiotic resources (minerals and hydrocarbons) (Costa et al., 2020, p.13).

New technologies, such as those that indicate gene expression in response to climate change, provide geochemical proxies for exposure and condition or use auditory, eDNA and animal tags to evaluate distributions, which could provide useful information. Mobile platforms and small-scale observatory facilities enable manipulative experiments, rate measurements and time-series photography, generating new perspectives. Deep-sea physical oceanographers, biogeochemistry, ecologists and fisheries experts will need to work together; besides, large-scale deep-ocean observing programs may need to be integrated (FAO, 2018, p. xxii-xxiii; Govindarajan et al., 2021, pp. 1–2).

Regional Fisheries Management Organizations (RFMO) play a major role in the management of international fisheries and their effects on ecosystems. They were created to promote long-term conservation and optimal utilization of fishing resources, thereby safeguarding marine ecosystems and meeting international commitments such as those set down in the UNFSA (FAO, 2018, p. 147). The conventions and agreements of the RFMOs define the parameters in which they operate and for the most part, this is limited to fisheries and their implications.

Monitoring catch, creating evaluations, establishing the proportion of the stock harvested, comparing this to reference points for sustainable utilization and ultimately imposing catch limitations to assure sustainability are all common practices in fisheries management (FAO, 2018, pp. 147–156). While fisheries management promotes biodiversity conservation by minimizing the effects of fisheries, biodiversity is also threatened by a variety of other factors.

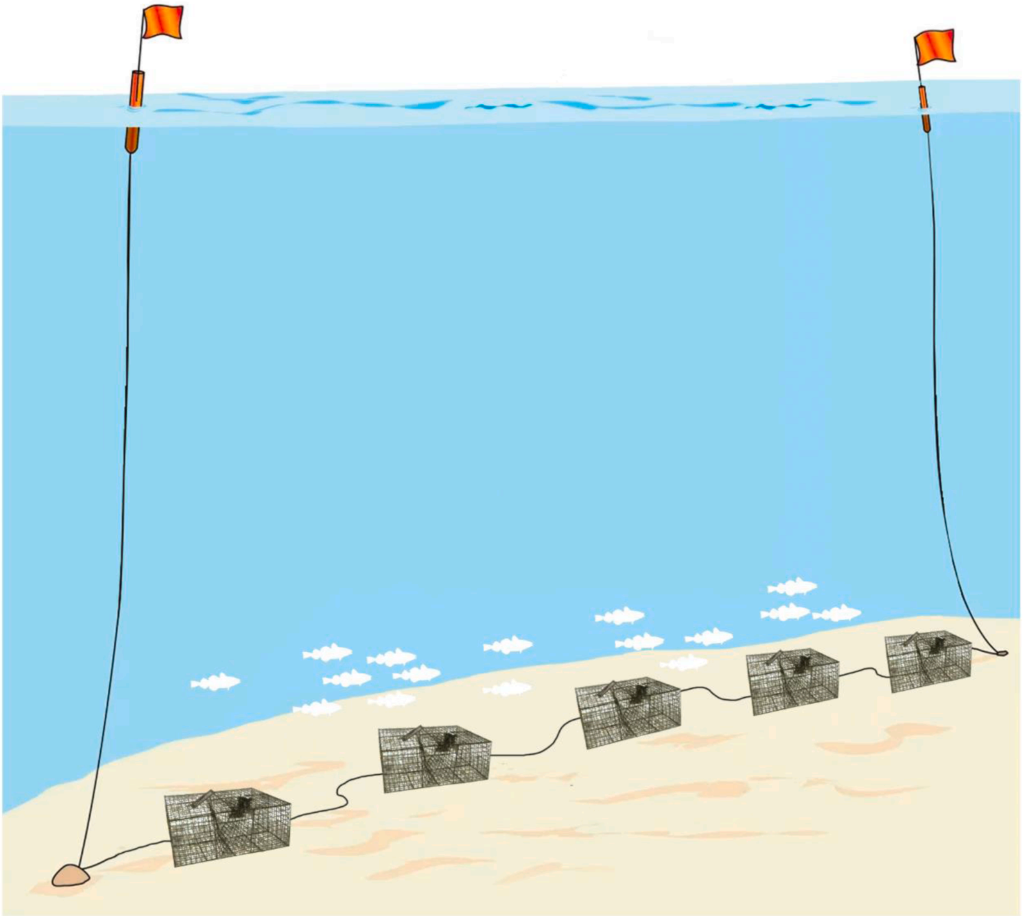

Fig. 9. Bottom-Set Pots (Authors' own illustration).

The most significant are probably global warming, ocean acidification and ocean deoxygenation. To maintain the health and productivity of the seas, partnerships must be formed and encouraged – which allow these broader concerns to be managed. Cooperation across jurisdictional borders, sectors (industry, research and regulators) and disciplines, as well as a forward-looking commitment to maintaining deep-sea ecosystem services, will be required for long-term sustainability (FAO, p. 159).

Even though it is challenging to think about different fisheries management practices, particularly on the high seas, scientists and managers should continue to collaborate with the industry to investigate new techniques in management, assessment and technology, particularly as climate change threatens the distribution and abundance of many fish stocks (FAO, 2018, pp. 156–159).

A pluralistic view envisaging a learning-by-doing outlook based on practical, diverse experiences around the world can assist future strategies. In this sense, promoting polycentric governance and community-based management of natural resources and commons (Gatto, 2022; Ostrom, 2010; Schlager and Ostrom, 1999; Ostrom, 1990). One shall, indeed, bear in mind that fishery grounds are typical commons and, as such, they risk overexploitation, degradation and depletion if unproperly regulated. Common-pool resources will return the most effective and just resource allocation due to local communities' communication, trust and reciprocity.

A viable alternative to fishing is aquaculture. Aquaculture provides a considerable part of total aquatic food and is increasingly used all over the world (FAO, 2020). However, if it is true that aquaculture may relieve fishery basins, environmental depletion and overuse of natural resources, the risk of unsustainable management of aquaculture is high (Harris and Roach, 2021). Sustainable and resilient aquaculture models are spreading worldwide and may furnish a valuable alternative to obsolete practices (Valenti et al., 2018; Subasinghe et al., 2009). This is the case for integrated multi-trophic aquaculture systems (IMTA), where several species are grown together (Khanjani et al., 2022) and aquaponics, where aquaculture is mixed with hydroponics (Kledal and Thorarinsdottir, 2018).

RFMO management measures can include climate change in various ways. Protocols for assessing the impacts of new fisheries can be applied more thoroughly, including the cumulative impacts of climate change and a more comprehensive review process before new fisheries can be authorized (e.g., controlling the vessel carbon dioxide emissions).

The necessary foundation of fishery assessments means accurate identification during and after fishing (prior to processing and/or reduction). This is particularly important for lanternfishes which are the dominant biomass component of deep-scattering layers. To provide early warning of the consequences of climate change, the monitoring and mapping of deep-sea fishing regions by gear and species linked with vulnerable marine ecosystems (VMEs) should be strengthened. In order to ground-truth models, verify predictions and detect regions approaching critical-point thresholds, more deep-ocean monitoring platforms are needed, particularly around existing and exploratory RFMO fishing zones and VME closures (Clark, 2001; FAO, 2018, p. 158).

6. Conclusion

Rising temperatures will increase stratification in the open ocean and acidity will reduce plankton's ability to form calcareous structures. This will affect the pelagic ecology and thus the global carbon cycle for the

Table 2
World Fisheries and Aquaculture Production, Utilization and Trade[1] (FAO, 2020, p. 3.).

	1986-1995	1996-2005	2006-2015	2016	2017	2018
	Average per year *(million tonnes, live weight)*					
Production						
Capture						
Inland	6.4	8.3	10.6	11.4	11.9	12.0
Marine	80.5	83.0	79.3	78.3	81.2	84.4
Total capture	86.9	91.4	89.8	89.6	93.1	96.4
Aquaculture						
Inland	8.6	19.8	36.8	40.0	49.6	51.3
Marine	6.3	14.4	22.8	28.5	30.0	30.8
Total aquaculture	14.9	34.2	59.7	76.5	79.5	82.1
Total world fisheries and aquaculture	101.8	125.6	149.5	166.1	172.7	178.5
Utilization[2]						
Human consumption	71.8	98.5	129.2	148.2	152.9	156.4
Non-food uses	29.9	27.1	20.3	17.9	19.7	22.2
Population (billions)[2]	5.4	6.2	7.0	7.5	7.5	7.6
Per capita apparent consumption (*kg*)	13.4	15.9	18.4	19.9	20.3	20.5
Trade						
Fish exports (in tons)	34.9	46.7	56.7	59.5	64.9	67.1
Share of exports in total production	34.3%	37.2%	37.9%	35.8%	37.6%	37.6%
Fish exports (in billion USD)	37.0	59.6	117.1	142.6	156.0	164.1

[1] World Fisheries and Aquaculture Production, Utilization and Trade1

[2] Utilization data for 2014-2018 are provisional estimates.

earth's living organisms, making climate change the most significant human impact on deep-sea resources (Coma et al., 2009; FAO, 2018, pp. 158–159). Mesopelagic fishes facilitate carbon sequestration in the deep ocean and therefore are key components of the BCP (Robinson et al., 2010). Without this pump, the partial pressure of atmospheric CO_2 would reach twice its current value (Maier-Reimer et al., 1996). However, the precise scale at which these carbon and nutrient cycles work across the mesopelagic is still unknown (St. John et al., 2016; Caiger et al., 2021, p. 776).

As the ocean's temperature and acidification increase, it is currently undefined to what extent the ecosystem services provided by the mesopelagic zone will be disrupted (Caiger et al., 2021, p. 776). Climate change has unique characteristics which demand new perspectives and management strategies. In a nonlinear approach, risks are likely to correspond with and be exacerbated by tipping points. This indicates that the effects might be considerably bigger, wider and more diversified than they would be if other fundamental changes were made (Cisco and Gatto, 2021).

The concentration of GHG emissions in the atmosphere determines the impact of climate change and there is presently no developed technology to reverse the process (NGFS, 2019, p. 4). The unpredictability of climate change is witnessed by critical scientific evidence. A notable case is the IPCC's announcement stating that the 1.5-degree mark may be reached in 2030, which is earlier than previously predicted (2050), requiring swift investments (IPCC, 2018).

The scale and character of future consequences will be decided by today's actions, which must follow a credible and forward-looking policy path, including governments, central banks and regulators, as well as financial market players, corporations and individuals (NGFS, 2019, p. 4). In fact, deep-sea fisheries do cause the extinction of benthic biodiversity and ecosystem services, with possible biogeochemical repercussions (Pusceddu et al., 2014). According to Merrett and Haedrich (1997), deep-sea fish stocks are considered nonrenewable resources. Therefore, these findings back up the call for rapid action to ensure the long-term sustainability of deep-sea fisheries management.

In order to catch sustainably mesopelagic fish resources, forward-looking management strategies must consist of species-level and population-level vital rates assessment (St. John et al., 2016). In general, the deep-sea fishery can lead to collateral costs of deep-water exploitation due to the bycatch of most species and can cause high mortality (Roberts, 2002, p.243).

Regarding the high costs of fishing equipment such as larger boats, specialist gear and long voyages, there is probably no possibility for a sustainable and economically viable deep-sea fishery (Roberts, 2002, p.244). In general, passive gears like traps and pots are regarded to have less severe environmental consequences and lower fuel requirements per kilogram of capture than trawls (Suuronen et al., 2012). Furthermore, increasing efforts to avoid the loss of gears might obtain better results (Suuronen et al., 2012; Ziegler and Valentinsson, 2008; Hornborg et al., 2016).

Besides, a transformation of subsidies from industrial to technology-equipped small-scale fishery seems to be economically, ecologically and socially more efficient. There may be an opportunity to fish from high water to deep sea, as human consumption would possibly not remove half a percent of the biomass from the mesopelagic zone and with a selective fishing method, the species of the epipelagic zone could possibly reproduce. However, further research concerning deep-sea fisheries and developed technologies that could provide less fuel and selective catching is needed.

Deep seas are largely unexplored and their management is seldom regulated. Without due governance rules, resources from mesopelagic areas risk being quickly plundered and degraded. However, deep seas are likely to be explored in the upcoming years and receive high investments. This will result in additional resource availability from these areas. Importantly, whether appropriately managed, this outlet may be manna for business, global food and nutrition security, becoming assets for resilience. However, important environmental and sustainability caveats shall be borne in mind for mesopelagic ocean explorations, targeting sustainable development objectives (Xiong et al., 2022). This will need tailored and long-sighted policymaking.

According to sustainable fishery management, additional actions are required since transformative approaches can make fisheries more sustainable. Therefore, the question of whether deep-sea fisheries are sustainable remains on the other hand, unanswered. Globally, mesopelagic ecosystems, particularly when it comes to biographical fish studies, are largely underexplored. Holistic approaches striving to reach blue growth/development goals are required.

Oceans sustainability is receiving attention but progress is yet meager (Andriamahefazafy et al., 2022). Sustainable development of waters will pass by sustainable practices in fishery and aquaculture management. Deep-sea fishery is at the forefront of this process since these areas are still largely unknown. Law, policy and governance are the cruces to achieving these objectives. To this end, it will be determinant to meet SDG 14.c – i.e. implementing and enforcing international sea law – and measuring "progress in ratifying, accepting and implementing through legal, policy and institutional frameworks, ocean-related instruments that implement international law" – SDG 14.c.1 (UN, 2015). Future scenarios for global food security and environmental preservation will also be shaped by sustainable and resilient management of deep-sea waters.

This inquiry contributed to the existing scholarship on fishery management by analyzing the sustainable management of deep-sea resources for fostering food and nutrition security. So far, this is the first attempt to review deep-sea fishery management and its impact on food security from a sustainability and resilience angle. The contribution is original and sheds light on barely explored research questions, policy and industrial capacities.

Numerous knowledge gaps exist, so this survey highlights the existing state of knowledge with a stronger focus on future research in the matter of deep-sea fishery (Caiger et al., 2021 p. 776). Additional research is needed in this meagerly explored field. This includes additional literature reviews supported by different methods, quantitative and qualitative inquiries on the topic, as well as game-theoretical, economic, governance and policy-oriented investigations on food security and deep-oceans sustainable management. Alternative techniques may be used in future papers – i.e. a scenario analysis, a fully-fledged SWOT analysis or PESTEL method, or CSR and ESG examination. Some other works may want to analyze alternative scenarios for deep-sea fishery management or look more closely at legal, regulatory or policy strategies – such as the formulation and possible repercussions of a moratorium on the issue.

CRediT statement

Conceptualization: AG; ERSZ. Methodology: AG. Software: n/a.. Validation: AG. Formal Analysis: AG. Investigation: AG. Resources: AG; ERSZ. Data Curation: n/a. Writing Original Draft: AG; ERSZ; SO; HK; NTNH. Writing: Review & Editing: AG. Visualization: AG; ERSZ. Supervision: AG; Project Administration: AG; ERSZ. Funding acquisition: n/a.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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