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Food for Thought

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Learning from the history of red shrimp fisheries in the Mediterranean to improve sustainability of deep-water bottom trawling

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Abstract

As deep-water red shrimp (DWRS) trawl fisheries gain importance in the Mediterranean, their impact on fragile deep-sea ecosystems requires careful management. We reviewed the historical development of DWRS fisheries in the Mediterranean to propose a harvest strategy that would enhance fishery sustainability, while preserving habitat and community integrity. We considered two representative typologies of DWRS fisheries: a domestic fleet operating within the Italian territorial waters of the Ligurian Sea, and a distant fleet operating mostly in international waters of the central-eastern Mediterranean and sharing shrimp stocks with non-European countries. Our proposed management approach is based on three main harvesting measures: (i) preventing the uncontrolled growth in number of trawlers, (ii) adopting a catch control regime, and (iii) identifying a network of deep-water areas designated alternately for fishing and conservation purposes. As with fisheries in other regions, new fishing grounds should be explored using "encounter protocols" to avoid areas hosting species indicators of Vulnerable Marine Ecosystems. Additionally, empirical indicators such as catch rate thresholds derived from fishers' experience, could be used to move from one fishing ground to another to avoid local depletion of DWRS abundance and a decrease in fishery profitability.

Keywords: domestic fisheries; distant fisheries; shared stock; fisheries management; harvest strategies; deep-sea ecosystems

Introduction

The collapse of coastal fishery resources worldwide, including in the Mediterranean Sea, has led trawl fisheries to expand to deeper waters to exploit more economically valuable concentrations of commercial stocks (Norse et al. 2012). However, deep-sea fishing is undoubtedly among the most controversial globally, as most deep-water species are long-lived, with low fecundity and slow growth rates. This makes them prone to quick depletion and slow recovery (Clark et al. 2016).

According to FAO (2017), the main target species of Mediterranean deep-sea trawl fisheries are the highly prized deep-water red shrimps (DWRS). These include the giant red shrimp, *Aristaeomorpha foliacea* (Risso, 1827), and the blue and red shrimp, *Aristeus antennatus* (Risso, 1816), generally harvested at depths of 400–800 m. In addition, deep water trawling at 200–500 m targets two other important deep water crustaceans—the deep-water rose shrimp, *Parapenaeus longirostris* (Lucas, 1846) and the Norway lobster, *Nephrops norvegicus* (Linnaeus, 1758). The main commercial bycatch of these fisheries is the European hake, *Merluccius merluccius* (Linnaeus, 1758).

In recent decades, there has been growing awareness of the need to safeguard natural resource renewability and habitat integrity. This has led to a gradual but significant change of viewpoint in the approach to fishing, with increasing emphasis on strategies that ensure long-term sustainability of catches while safeguarding Essential Fish Habitats (EFHs) (Garofalo et al. 2011, Rijnsdorp et al. 2012, Colloca et al. 2015) and Vulnerable Marine Ecosystems (VMEs) (Maggs et al. 2013, Lauria et al. 2017, Rowden et al. 2019). In heavily exploited fishing grounds, epibenthic fauna occurrence, which plays a relevant role in demersal ecosystem structure and functioning, is very reduced and often confined to sparse patches on rough bottoms (Clark et al. 2016). As a result, many studies have emphasized the importance of protecting the three-dimensional structure of sea bottom and creating unfished *refugia* to rebuild and maintain stock productivity (Sinclair et al. 2002, Caddy 2014). Protecting the integrity of critical habitats in terms of both EFHs and VMEs has recently become part of EU policies (Common Fishery Policy, CFP; Marine Strategy Framework Directive, MSFD; Marine Spatial Planning, MSP; and Habitat Directive, HD) and recommendations of Regional Fishery Management Organizations (RFMOs). In the Mediterranean, the FAO General Fisheries Commission for the Mediterranean (GFCM 2007) has established nine Fisheries Restricted Areas (FRAs) where specific fishing activities are temporarily or permanently banned or restricted to improve the exploitation patterns of main fisheries target species and conservation of EFHs and VMEs. One

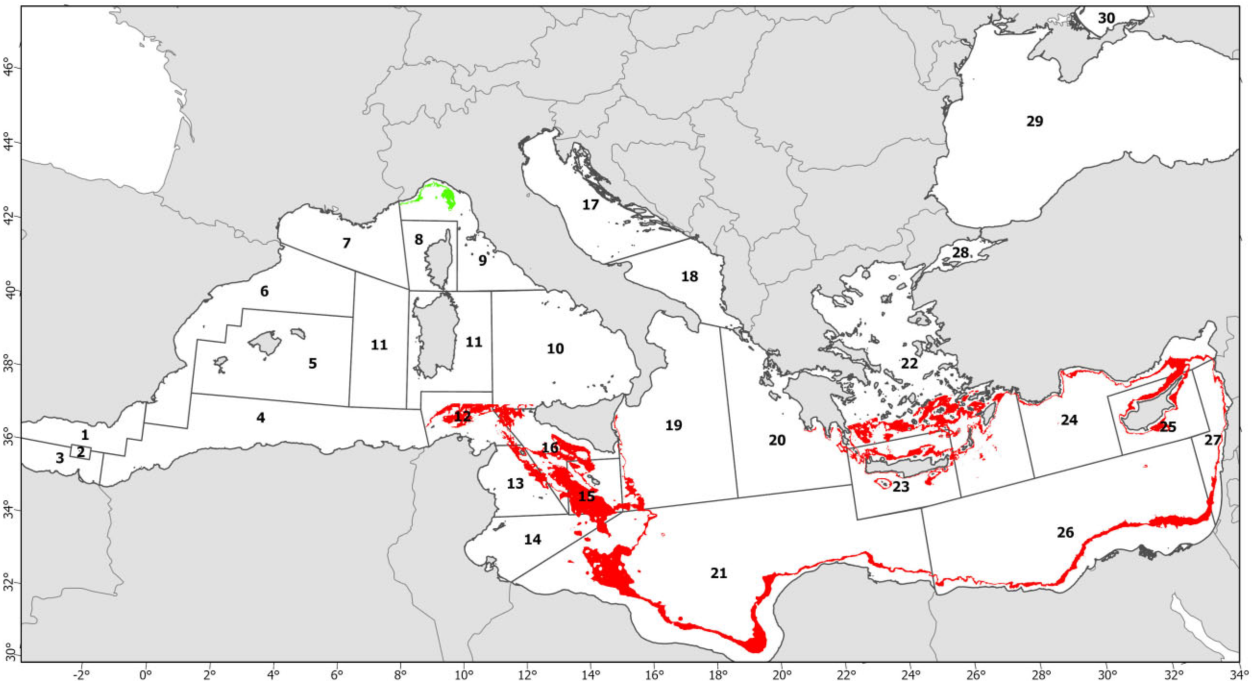

Figure 1. Sea bottoms between 400 and 800 m represent the operational areas of the Ligurian (“domestic” fleet in GSA9) and Sicilian (“distant” fleet in GSAs 12–16 and 21–26) bottom trawlers targeting the DWRS. The division of the Mediterranean and Black Sea into Geographical Sub Areas (GSA) labelled from 1 to 30 is also shown.

of such FRAs includes all waters deeper than 1000: it is a large deep-water FRA where the use of towed dredges and trawl nets is banned to protect deep-sea benthic ecosystems (https://www.fao.org/gfcm/data/maps/fras/en/).

Given the context described, our analysis aims to (i) review the history of two exemplary Mediterranean DWRS fisheries, (ii) summarize evidence on their impact on demersal resources and benthic habitats, and (iii) propose perspectives to make them more sustainable by considering both DWRS stock productivity and deep-water biodiversity conservation. In particular, our analysis relies on literature, personal observations, and fishers' knowledge gathered following the development and maturity of two different DWRS fisheries: the “domestic” trawlers operating off the coast of the Ligurian Sea (northern sector of the Geographical Sub Area, GSA 9; GFCM, 2007), within or close to the territorial waters, and the “distant” trawlers of Mazara del Vallo (also referred to as Mazara trawlers), based in the south-western coast of Sicily (GSA 16) in the Strait of Sicily (SoS, south-central Mediterranean), but operating from the Sardinia Channel to the Aegean and Levant Sea in the eastern Mediterranean (Fig. 1).

The “domestic” fisheries in the Ligurian Sea

The history of DWRS fishery in the Ligurian Sea, up to the end of the 1980s, has been reconstructed by Orsi Relini and Relini (1985) and Relini and Orsi Relini (1987). During the 1930s, fishers began exploiting red shrimp on the outer shelf-upper slope (200–300 m), catching between 100 and 200 kg/boat/day. During this developing phase, fishing took place mainly during the summer months and the catch was composed of both *A. antennatus* and *A. foliacea*. Following the halt in fishing activities during World War II (1940–1945), catches increased to reach values as high as 1000 kg/boat/day. However, this level of catch decreased significantly until the mid-1950s, as DWRS became scarce on epibathyal bottoms (200–450/500 m). To cope with this reduction, fisheries began to exploit mesobathyal layers (450/500–800 m), mainly fishing *A. antennatus* with catches of 100 kg/boat/day. From 1956 to 1980, *A. foliacea* became increasingly rare, and the quantity of *A. antennatus* progressively decreased until the DWRS fishery collapsed.

In 1985, the first signs of recovery were observed, with the arrival of large-sized shrimps to the fishing grounds (Orsi Relini and Relini 1986). During the summer of 1987, an exceptional recruitment of *A. antennatus* was observed on trawlable bottoms between depths of 450 and 700 m off the Ligurian coast, which led to the extension of the fishing season from the traditional summer months to year-round fishing (Orsi Relini and Relini 1988). This exceptional recruitment, formed by individuals spanning different age classes, sustained the fisheries for about 10 years although catch rates gradually declined until the late 1990s. The mean catch rate for the S. Margherita Ligure fleet, the most important trawler fleet operating along the eastern Ligurian coast (Fig. 2), declined from about 35 kg/boat/day in 1987 to nearly 18 kg/boat/day in 1996 (Fiorentino et al. 1998). Similarly, the catch rates of Sanremo trawlers, the primary fleet on the western coast, decreased from about 31 kg/boat/day during 1995–1996 (Relini et al. 1998) to ∼18 kg/boat/day during 1997–1998. Another significant recruitment event of *A. antennatus* occurred in the Ligurian bottoms between 2009 and 2010, with the average CPUE reaching levels comparable to those of 1988, at 32 kg/boat/day (Alessandro Mannini, personal communication). This new recruitment of shrimp once again sustained the fisheries for many years, with the CPUE decreasing to about

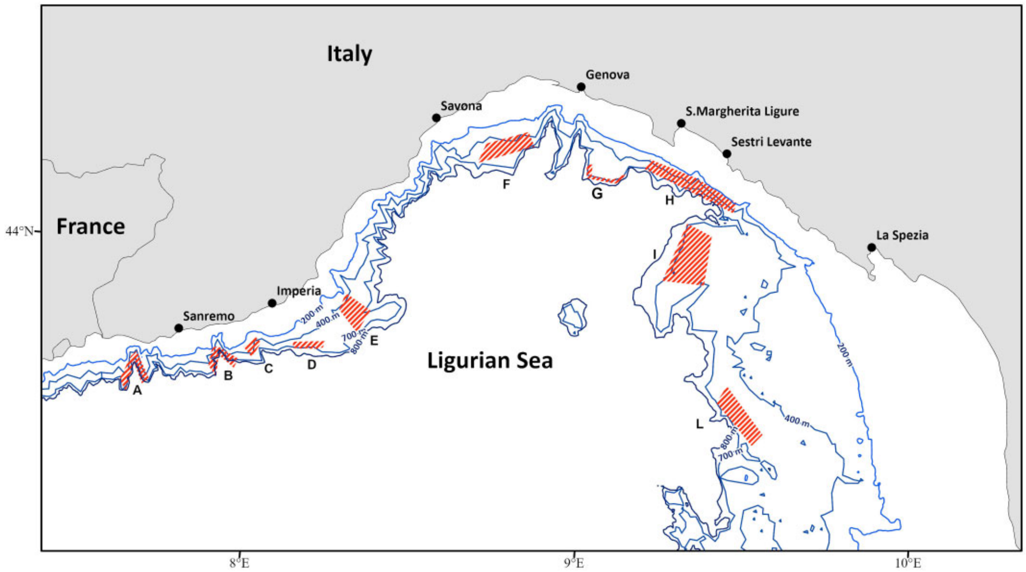

Figure 2. Principal fishing grounds of *A. antennatus* in the Ligurian Sea. (A) Ventimiglia Canyon, (B) San Remo Canyon, (C) San Lorenzo Canyon, (D) Vapore Bank, (E) Banco Bank (western Riviera), (F) between Genoa and Savona Bank, (G) Banchetto Bank, (H) Di terra le rame Canyon, (I) Di fuori le rame Bank, and (J) Banco Bank (eastern Riviera) (redrawn from Fiorentino et al. 1998).

17 kg/boat/day in 2019–2020 for the S. Margherita Ligure fleet, and to about 19 kg/boat/day for the Sanremo fleet (Fulvio Garibaldi and Luca Lanteri, personal communication).

During the mid-1980s, there were ∼35 deep-water trawlers operating in the Ligurian Sea (Relini and Orsi Relini 1987). By the late 1990s, the DWRS fishery in the same area was carried out by 12–15 "domestic" trawlers fishing on few hauls along the open slope and the trawlable flanks of submarine canyons (Fig. 2). Vessels typically fished the same track for months, proceeding in line "like ants" and keeping a distance of about 2 nm from each other (Orsi Relini et al. 2013). This fishing modality, which is still in use, implies that the fishing grounds act as a sort of attractor for DWRS, with new shrimps reaching the fishing grounds from adjacent areas to replace those that were caught the day before. Currently, a total of 18 trawlers, based in the ports of S. Margherita Ligure and Sanremo, target DWRS in the Ligurian Sea year-round. Two additional trawlers from the ports of Savona and Bordighera target DWRS occasionally during summer (Fulvio Garibaldi and Luca Lanteri, personal communication). Trawlers from S. Margherita Ligure and Sanremo typically fish for about 9–10 h/day. Information on the evolution of fishing effort, in terms of the number of trawlers and fishing days targeted to DWRS, showed a decrease in the fishing effort for the S. Margherita fleet from 1620 fishing days (fds) in 1995 (10 trawlers) to 1395 fds in 2020 (nine trawlers), while an increase resulted for the Sanremo fleet from 1281 fds in 1995 (seven trawlers) to 1602 fds in 2020 (nine trawlers). Analyzing the two case studies in the Ligurian Sea, the fleets of S. Margherita and Sanremo, each comprising 9–10 deep-water trawlers and exhibiting a fishing effort of about 1400–1600 fds, resulted able to maintain an average annual CPUE of at least 17–19 kg/boat/day.

Based on stock assessment, an overfishing status of *A. antennatus* in the central eastern Ligurian Sea, exploited by the Santa Margherita trawlers, has been detected using length cohort analysis (LCA) since the 1990s (Fiorentino et al. 1998). More recently, the overfishing status with a low level of biomass was confirmed using an a4a assessment model and assuming a single stock unit of *A. antennatus* in the Tyrrhenian and Ligurian Sea (GSA 9, 10, and 11) (STECF 2021). Despite this, the presence of a limited fleet of trawlers specialized in DWRS fisheries in the port of Santa Margherita Ligure, which has slightly reduced the fishing effort over the last 25 years, has resulted in a relative stability in CPUE and has prevented a fishery collapse similar to the one that occurred in the early 1980s. The exploitation of spatially limited fishing grounds, which serve as a "sink" and are likely replenished by DWRS from adjacent "source" areas, can maintain profitable shrimp populations, provided that the" source" areas contain enough shrimp to replace those caught. The mechanism proposed by Sardà et al. (1994) suggests a migration of *A. antennatus* from the deep escarpment to shallower areas, primarily through canyons that serve as habitats where the species tends to aggregate. This mechanism was later reaffirmed by Relini et al. (2000, 2004) when they examined the migration patterns of *A. antennatus* in the Ionian Sea. Through tagging and recapture experiments, they deduced that the species exhibited displacements ranging from 2 to 20 km/month. The impact of deep-water fisheries on benthic communities in the Ligurian Sea is a well-described issue in the literature regarding both soft and hard bottoms (Cattaneo Vietti et al. 2010, Bo et al. 2014). These impacts are due to the mechanical effects of bottom trawling, which reduces the coverage of habitat-forming species, such as cnidarians and sponges, affecting the diversity and abundance of associated organisms, and produces the sediment resuspension causing habitat disturbance. For instance, D'Onghia et al. (2003) reported the disappearance of the cnidarian *Isidella elongata* from the soft bottoms exploited by DWRS fisheries in the western Ionian Sea, and its occurrence in the eastern Ionian Sea not exploited by deep water trawling. Similarly Maynou and Cartes (2012) showed that in the western Mediterranean, where *I. elongata* facies were once common, bottom trawling directly affected the biological assemblages where DWRS live by removing habitat-forming corals, decreasing invertebrate species diversity, and potentially reducing fisheries production in the long term. Historical accounts and fisher's maps for the eastern Ligurian Sea have reported the occurrence of cold water coral (CWC) reefs, mainly formed by *Madrepora oculata* (Linnaeus, 1758), between depths of 200 and 500 m. However, recent research by Fanelli et al. (2017) has described the degradation of these reefs owing to the high pressure of deep-water trawling. The authors also described the presence of dense populations of living colonies of *M. oculata*, reaching 1 m in height, on the flanks of the canyons in the eastern Ligurian Sea at depths between 525 and 575 m. These populations were not impacted by trawling but were overturned or entangled by long-lines. Based on the discovery of new CWC reefs that are not yet heavily impacted by fishing, the authors suggested creating a network of high-seas/deep-sea marine protected areas to safeguard areas where CWCs still occur. This approach echoes the proposal put forward by D'Onghia et al. (2016) and (2019) in the Ionian Sea, which was grounded on a comprehensive assessment of the role of CWC habitats as EFH, and their significance for the renewal of fishery resources.

The "distant" fishery of the Mazara del Vallo fleet

The historical development of the DWRS fishery of the Mazara fleet, which is one of the main Mediterranean trawler fleets (Pinello et al. 2018), could be considered the main case of large-scale spatial dynamics of fisheries in the Central and Eastern Mediterranean, characterized by massive fleet movements linked to resource abundance and fishing profitability, as well as forced by geopolitical events.

Mazara fleet began deep-water trawling in the SoS in the 1960s, with the exploitation of deep-water rose shrimp, *P. longirostris*, as the main target species (Levi et al. 1995). The fishery developed mainly along a north–south axis, from Sicily to Tunisia, exploiting the fishing grounds in GSAs 12, 13, and 16 (Knittweis et al. 2013). In the late 1970s, the fleet started to develop DWRS fisheries targeting almost exclusively *A. foliacea*, prompted by its abundance and high commercial value. After an initial phase, the fleet expanded its fishing areas towards the south-eastern portion of the SoS off the Libyan coasts (Ragonese 1995) (Fig.3).

The described expansion of DWRS fisheries was due to a progressive decline in *A. foliacea* abundance in the northern sector of the SoS. According to Ragonese et al. (1994a), the catch rates from trawl surveys in the area decreased from 25 kg/h in the early 1960s to 8 kg/h in the middle 1970s, 5 kg/h in the mid-1980s, and 3 kg/h in the early 1990s. Catch rates continued to decrease to 1.5–2 kg/h in the early 2000s, about 1 kg/h in the early 2010s, and 0.3–0.5 kg/h at the beginning of the 2020s (CNR IRBIM database). Besides the decrease of survey catch rates, the worsening of the DWRS in the SoS was also proven by the stock assessments. According to Ragonese et al. (1994b), the stock of *A. foliacea* was in sustainable exploitation ($E = F/Z < 0.5$) up to the mid-1980s. Later, Bianchini et al. (2003) reported a deterioration of the stock from 1985 to 1993, suggesting the reduction in fishing mortality to move the stock exploitation towards more sustainable level. Furthermore, Ragonese et al. (2002) reported that the diamond mesh size used in the SoS in the mid-1990s (32–36 mm opening) caught a great amount of juveniles and recommended the use of a mesh size of 56 mm opening to allow the escape of juveniles without compromising the catch of larger and higher-prized shrimps. A more recent assessment of the stock status of *A. foliacea* in the SoS (Gancitano et al. 2011) recommended halving the fishing mortality to achieve more sustainable harvesting (Fig. 4).

The declining productivity of DWRS fisheries in the entire SoS (GSA 12, 13, 14, 15, 16 and western GSA 21 in Fig. 1) since the early 2000s, combined with the absence of deep-water trawling beyond 400–500 m in the Aegean and Levant Sea (GSA 22, 23, 25, and 26) (Vasconcellos 2013), prompted some more enterprising captains of the Mazara fleet to explore the "virgin" bathyal bottoms of the eastern Mediterranean in 2004 (Garofalo et al. 2007).

Initially, four to six trawlers from Mazara del Vallo working off the Libyan coast moved to waters around Crete and gradually extended their operations eastward, reaching deep-waters in front of Turkey, Cyprus, and Egypt (Fig. 5). This displacement was also related to the need to abandon the fishing grounds in front of Libya after the extension of the national fisheries protection zone in that area from 12 to 74 NM from the coastline in 2005. As a result, by 2006, the range of action of the Mazara deep-water trawlers had extended to a significant portion (GSAs 22–26) of the eastern Mediterranean.

During 2004–2008, the distribution of commercial CPUE showed important differences between the fishing grounds of the Central and Eastern Mediterranean (Fig. 6) (Garofalo et al. 2007, Vitale et al. 2019). The very low CPUE observed in the western fishing grounds of GSA 21 was most probably due to the high fishing pressure exerted there in the late 1990s to the mid-2000s, when up to 50 trawlers targeting DWRS operated in the "Deserto" area during summer (fishing captain Maurizio Giacalone, personal communication). Conversely, the CPUE in the easternmost areas, which have experienced recent and very low fishing pressures, could be considered representative of the catch rates achievable from a virgin stock in the eastern Mediterranean. This CPUE response to the exploitation history of DWRS aligns with Garofalo et al. (2007) findings, showing that catches in GSA 12 and western GSA 21 comprised mostly small shrimps, while the largest shrimps represented the main catch fraction in GSA 15, eastern GSA 21, and GSA 24.

When examining the period from 2009 to 2013 (Fig. 6), it becomes evident that there was an increase in CPUE in GSA 21 and a decrease in the easternmost fishing grounds.

This pattern can be attributed to an unintentional yet informative test of stock rebuilding due to the cessation of DWRS exploitation that occurred in western GSA 21, following the promulgation of the Libyan fishing protection zone (up to 74 miles from the coastline) in 2005. During the political instability that occurred after the Libyan Civil War of May 2011, Mazara trawlers returned to fishing for red shrimp in the fishing grounds within the Libyan fishing protection zone, in the absence of control by the Libyan authorities. According to analyses of VMS data by De Angelis et al. (2020), about 40 distant trawlers operated in the fishing grounds of GSA 21 (off the Libyan coast) in 2011. Specifically, the trawlers exploiting the "Deserto" fishing grounds were catching up to 300–350 kg/day of large-sized red shrimp in May 2011. However, catch rates dropped to 140–150 kg/day in July 2011 (fishing captain Antonio Genovese, personal communication) and further to 120–100 kg/day in December 2011 (fishing captain Maurizio Giacalone, personal communication). According to

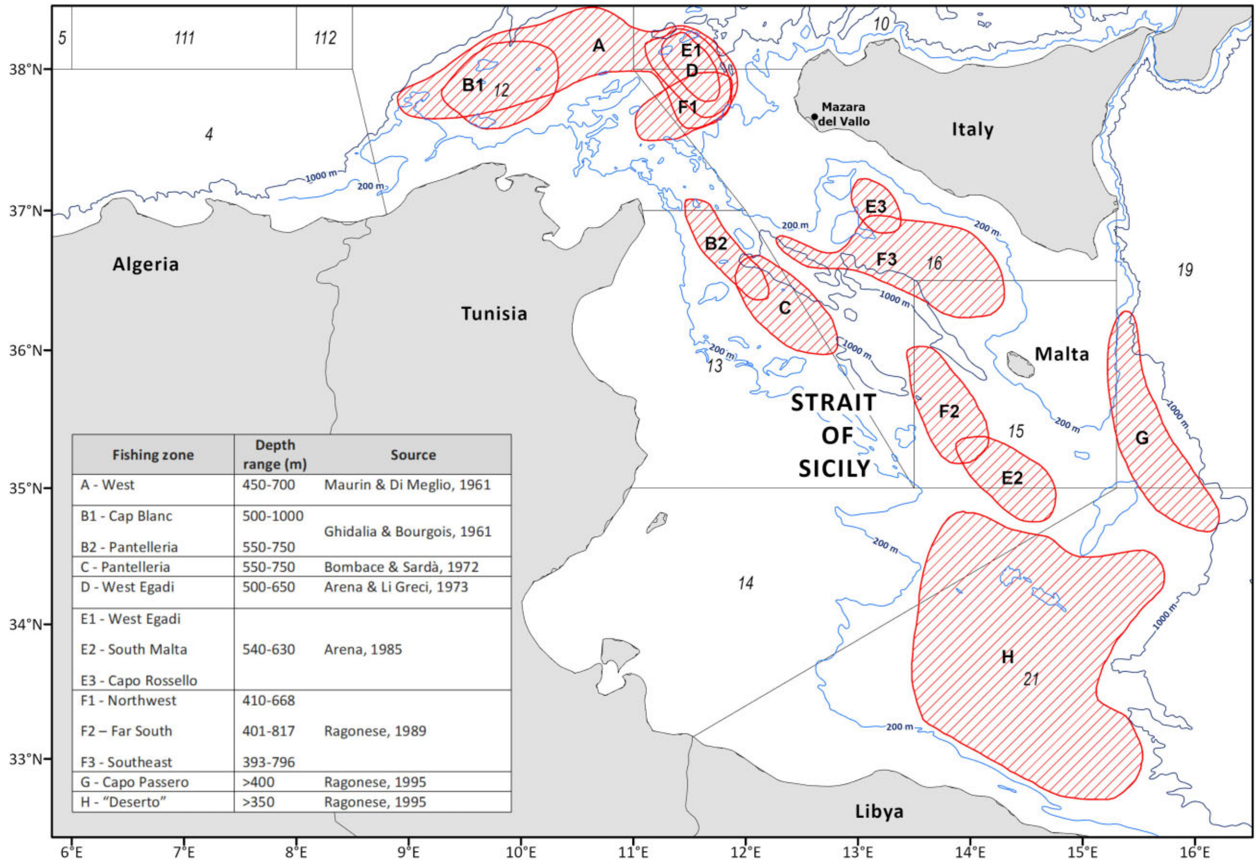

Figure 3. Main fishing areas for giant red shrimp in the Strait of Sicily described by various authors up to the 1990s (modified from Ragonese 1995). The geographical sub areas are also shown.

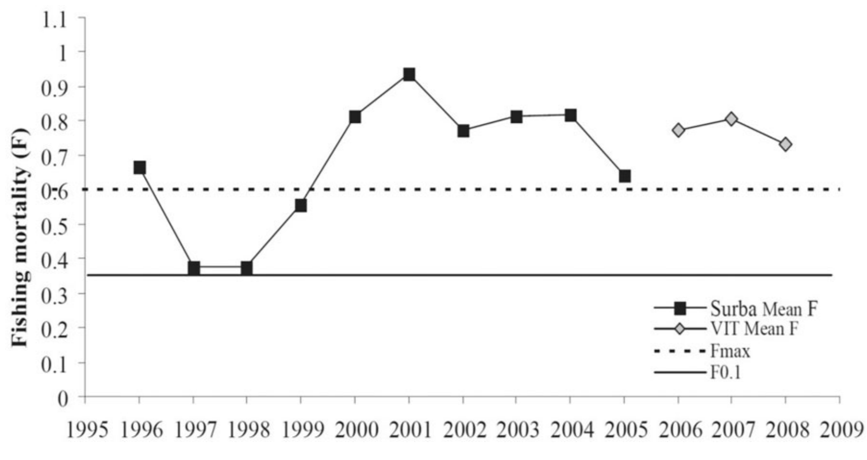

Figure 4. Trend of fishing mortality (F) of *A. foliacea* in the Strait of Sicily. The time series was constructed by integrating results from SURBA (Beare et al. 2005) and VIT (Lleonart and Salat 1997) stock assessment methods. The Biological Reference Points are the intermediate values between YIELD and VIT package (from Gancitano et al. 2011).

trawler owners (Paolo Giacalone, personal communication), revenue per day dropped by ~59% from May 2011 to December 2011. At the beginning of 2012, there were only 10 trawlers from Mazara fishing in the "Deserto" grounds. In other words, the unrestricted access to the DWRS resource caused, in about 7 months, the depletion of a stock that took about 6 years to rebuild.

The depletion of the DWRS stock in GSA 21 gave a new impulse to the fleet that shifted towards the eastern basin. In 2017, about 20 trawlers from Mazara were fishing DWRS in the Aegean Sea (north of Crete; GSA 2), around Cyprus (GSA 25), and off the Lebanon coast (GSA 27). Typically, the fishing season started in early March and ended in late November. The fishing grounds were located between 600 and 750 m deep. The number of hauls per day was 3–4, with each haul lasting about 5 h. The highest catch rates (up to 120 kg/haul) were obtained around midday (from 10 a.m. to 4 p.m.). This diel pattern is consistent with available information on DWRS

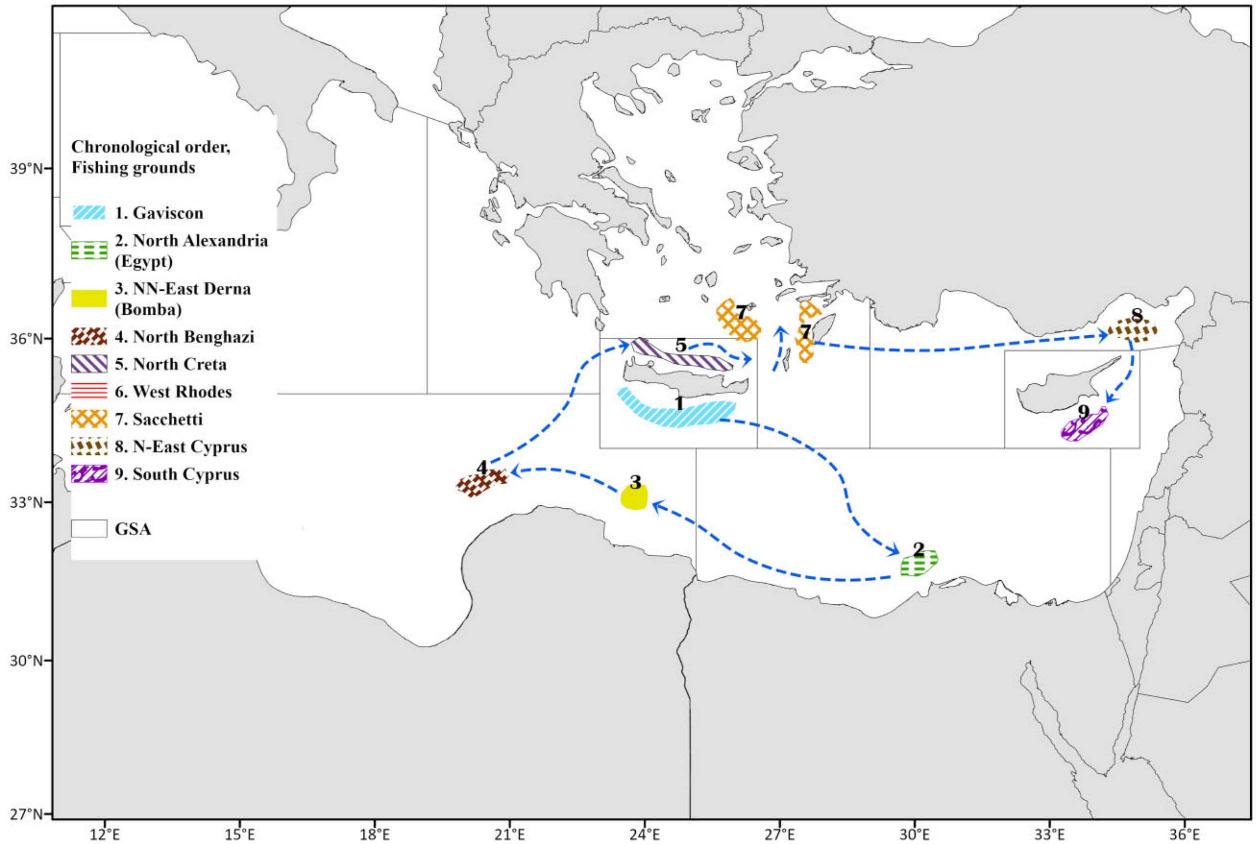

Figure 5. Chronological exploration of new DWRSF fishing grounds, from 2000s to date, in the eastern Mediterranean basin, according to Captain Domenico Asaro from Mazara del Vallo (redrawn from Vitale et al. 2019).

catchability (Bianchini et al. 1998), and lights are currently being used on trawl nets to increase catches during the night (up to 40 kg/haul). Every 20–30 days, the catch frozen onboard was landed on Crete, Rhodes, or Cyprus and then shipped to Mazara in refrigerated trucks and marketed throughout Italy (Pinello et al. 2018).

The DWRS fishery in the Eastern Mediterranean has been historically dominated by the Italian fleet (Vasconcelos 2013), allowing for a degree of self-regulation of fishing activities until recent years. In particular, Sicilian fishers informed the authors that they used to change fishing areas when the catch rate dropped below 30 kg of DWRS per haul. Based on their experience, this occurred when more than three to four trawlers were operating in the same fishing grounds. However, the recent involvement of new fleets into DWRS fisheries from emerging countries like Egypt, Tunisia and Turkey each characterized by specific socio-economic contexts and fishery regulations, has made this form of self-regulated fishing by the Mazara trawlers ineffective.

Noteworthy, the international demand for DWRS rapidly increased in last years, leading to significant increases in landings by the Mazara fishing fleet. Landings of *A. foliacea* increased from 780 tonnes in 2004 to 1490 tonnes in 2016, while *A. antennatus* landings rose from 180 tonnes to 400 tonnes over the same period (Pinello et al. 2018).

Several studies have investigated the impact of DWRS trawling on benthic assemblages at both the population and community levels in the central-eastern Mediterranean. Dimech et al. (2012) compared trawled and nontrawled sites within the Maltese 25 nm Fisheries Management Zone (GSA 15) and found no differences in the biomass indices of *A. foliacea* and *Etmopterus spinax* between the two areas. However, the biomass of other species, including *Plesionika martia*, *N. norvegicus*, *Helicolenus dactylopterus*, and *Galeus melastomus*, was 4, 16, 6, and 2 times higher, respectively, in the non-trawled compared to the trawled sites.

Similarly, Vitale et al. (2014) compared the abundance and size structure of long-lived fish sensitive to fishing effort, such as the silver roughy, *Hoplostethus mediterraneus*, in different DWRS fishing grounds of the Mazara fleet across the Central and Eastern Mediterranean. Their findings showed that the presence of silver roughy has been reduced and includes only small individuals in fishing areas subject to high fishing pressure for long periods. Conversely, in areas subject to moderate fishing pressure, the species had abundances and sizes comparable to those observed in areas not affected by bottom trawling.

Lauria et al. (2017) investigated the impact of DWRS fishery on epi-benthic cnidarians in the southern Sicily (GSA 16). The authors found that the cnidarian *I. elongata*, an indicator species of deep-water VMEs, occurs exclusively where trawling is low or absent, whereas the other more resilient deep-water cnidarian species, *Funiculina quadrangularis*, seems to survive even on trawled grounds. More recently, Carbonara et al. (2020) showed that there is an overlap of *I. elongata* hotspots with nursery and spawning areas of *A. foliacea*, *A. antennatus*, and *G. melastomus* in the South-Central Tyrrhenian (GSA 10) and Southern Adriatic (GSA 18). They observed no significant variation in species density over time in the South-Central Tyrrhenian, whereas

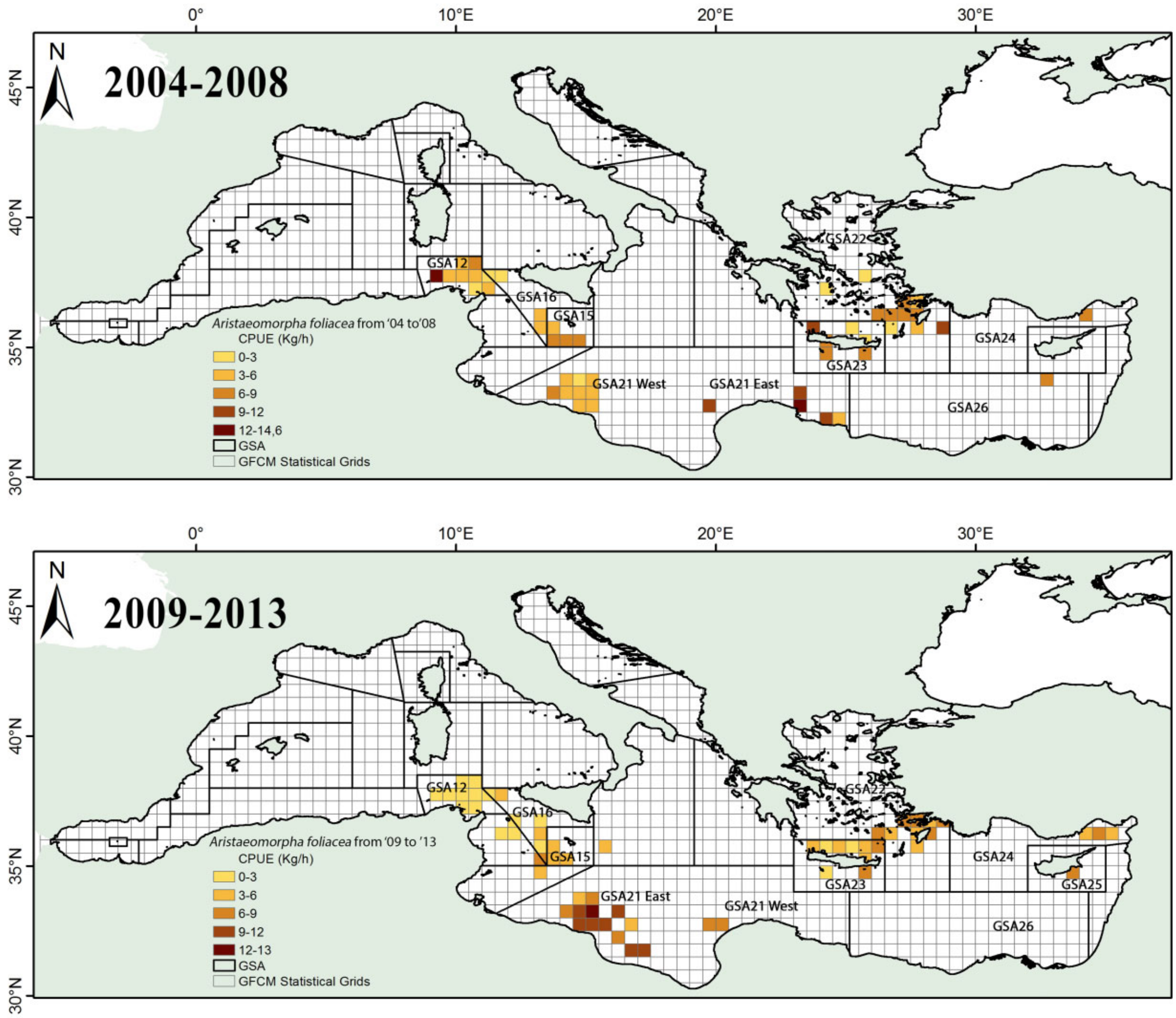

Figure 6. Catches per unit effort of the giant red shrimp, *A. foliacea*, in various GSAs exploited by the trawlers of Mazara del Vallo. The data is presented separately for the periods 2004–2008 (top) and 2009–2013 (bottom) (redrawn from Vitale et al. 2019).

the colonies were larger, but showed a decreasing trend over time in the Southern Adriatic.

Discussion

The management of DWRS in the Mediterranean has been the subject of extensive debate, and this paper provides a comprehensive review of the historical development of two distinct deep-sea trawl fisheries, which can be considered paradigmatic of the exploitation of these stocks. The synthesis of available information forms the basis for proposing a management approach that aims to ensure sustainable exploitation while mitigating negative ecological impacts. While our contribution primarily focuses on the effects of fishing on DWRS stocks and their associated communities, it is important to note that the literature also acknowledges other factors that influence the population dynamics of DWRS in the Mediterranean. Relini and Orsi Relini (1987) discussed potential factors, including changes in the thermohaline or turbidity characteristics of water masses, the decline in ecological quality of slope bottoms, and recruitment failure due to predation and parasitic infections, but did not propose the most plausible explanation. An inversion in the relative abundance of the two red shrimp species in the Ionian Sea was attributed to temporary changes in hydrographic conditions by Capezzuto et al. (2010), with *A. foliacea* being more abundant than *A. antennatus* during periods characterized by warmer and saltier seawater. Later, Amores et al. (2014), while investigating the relationships between the abundance of deep-water fauna, including DWRS, and oceanographic processes off the Catalan coast, reported that surface vorticity episodes could reach the bottom, causing sediment resuspension. The related increase of bottom water turbidity would produce a displacement of *A. antennatus* from the fishing grounds towards deeper waters. Similar responses have been observed during downslope shelf dense water cascading in submarine canyons, suggesting that oceanography plays a significant role in modulating the accessibility of DWRS to fishing exploitation (Amores et al. 2014). More recently, Masnadi et al. (2018) demonstrated that fishing could play a crucial role in shaping the spatial distribution of DWRS in the Ligurian and Tyrrhenian Seas. *Aristeus antennatus* predominates in areas and periods characterized by high fishing effort, which could be attributed to the greater resilience of blue and red shrimp to fishing impact compared to the red shrimp. This higher resilience could be due to its wider and deeper distribution (Sarda et al. 1994) and higher fecundity with respect (Kapiris and Thessalou-Legaki 2006) to *A. foliacea*. Conversely, the prevalence of *A. foliacea* has been found related to higher temperatures, confirming that its spatial distribution and abundance are primarily driven by sea water temperature.

Shifting the focus to the aspects of fisheries concerning the state and management of DWRS stocks in the Mediterranean, Vasconcellos (2013) reported that the capacity of the fleets engaged in DWRS fisheries in the Strait of Sicily and the Eastern Mediterranean (the Ionian, Aegean and Levantine Seas) in 2011 amounted to about 171 and 13 vessels for Italy and Malta, respectively, with an additional four trawlers from Greece and Turkey. The official landings by the Italian vessels, including the Mazara trawlers, amounted to 2000 tonnes, while those by Malta totaled 32 tonnes, and Tunisian trawlers amounted to 10 tonnes. Data for Greece, Turkey, Egypt, and Cyprus were unavailable at that time. It should be noted that at the end of the 2000s, almost all of the DWRS yield of the Strait of Sicily and the Eastern Mediterranean was due to the Italian fleet, with 75% coming from Sicilian trawlers and most of the remaining catch from the Apulian fleet (southern Italy), which operates mainly in GSA 19 and GSA 20 (Ionian Sea). In the middle of 2010s (2015–2016), the DWRS landing by the Italian fleet remained quite constant, ranging between 2000 and 2100 tonnes. Over time, the near-exclusivity of DWRS yield attributable to the Italian fleet has been progressively reduced by the entry into the "scene" of an increasing number of trawlers from other countries. Many of these trawlers come from non-EU emerging countries of the south-eastern Mediterranean (Egypt, Tunisia, and Turkey), which have very different socio-economic conditions compared to EU countries (Ben Arfa et al. 2022). Ibrahim et al. (2011) reported information on an exploratory survey off the Egyptian coast as a preliminary evaluation of the DWRS abundance in view of the exploitation of the resources by the Egyptian fleet. After this scouting phase, the Egyptian fleet suddenly developed a DWRS fishery for the international market, with catches of ∼500 tonnes in 2015, 750 tonnes in 2016, and 990 tonnes in 2017, although the CPUE per day per boat decreased from 160 kg in 2016 to 105 kg in 2017 (El-Haweet et al. 2018). According to fishers' information,, the Egyptian fleet targeting DWRS in the Eastern Mediterranean amounts to over 100 vessels. Notably, when a stock is fished for the international market under open access by fleets with varying operating costs, the fishing activities of the fleet with higher costs become economically unsustainable (Nielsen et al. 2014). Furthermore, non-EU countries generally do not have the same comprehensive monitoring and control systems for catches, effort, and gear adopted by European countries (Reg. (CE) 1224/2009). The high costs of effective management systems to pursuing sustainable fishing has recently been emphasized by Hilborn et al. (2020). In particular, when compared to intensively managed regions, less-developed fisheries management regions have, on average, three times higher harvest rates and half of the optimal abundance of assessed stocks.

Based on evidence gathered from the Ligurian DWRS, which has been exclusively exploited by a single country fleet operating mainly in territorial waters for almost 90 years under a framework of progressively improved controls on fishing capacity and effort, it appears that effective regulation of fishing capacity and effort could be the key to achieving long term sustainability of deep-water fisheries. On the other hand, the lessons learned from the case of the Mazara distant fishery, operating in the international waters of the central-eastern Mediterranean Sea, highlight that (i) the unregulated increase in fishing capacity and effort produces a strong depletion of DWRS productivity (from the middle 1980s to the middle 2000s) reducing fishery profitability; (ii) the self-managed regulation of fishing effort by a few trawlers that belong to the same fishing community (from the middle 2000s to 2015) and carry out rotations of fishing grounds as soon as an agreed minimum CPUE threshold is achieved, seems able to maintain the sustainability of DWRS fisheries; and (iii) this self-management approach has proven ineffective when no control over the access to the fishery is in force and the DWRS stock becomes exploited by different countries with different fishing patterns and levels of socioeconomic development (from 2015 to the present day). In this last case, the implementation of an agreed upon management system regulating the overall fishing capacity and the effort exerted on the stock is essential, albeit challenging to be achieved in the context of shared stocks exploited in international waters (McWhinnie 2009). However, it is of utmost importance that the conclusions derived from the examination of the historical performance of both the domestic and distant fisheries are supported by additional scientific evidence. This will serve to strengthen the validity and reliability of the findings, ensuring a more robust understanding of the sustainability of these fishing types.

As evidenced by the histories, owing to the high sensitivity of DWRS to overfishing, countries involved in their fisheries should avoid open access to fishing and reduce the risk of fleet overcapacity. To prevent free access to the fishery from bringing the DWRS stock to collapse, and taking into account the debate within the General Fisheries Commission in the Mediterranean (GFCM), the European Union has adopted Regulations (UE) 2022/110 and UE 2023/195, which establish fishing opportunities in terms of fishing effort and catch limits for DWRS fisheries in the western (GSA from 1 to 7) and central Mediterranean (GSA from 9 to 11), respectively. In 2022 the GFCM approved three recommendations for establishing Multiannual Management Plans (MAPs) for DWRS fisheries in the Strait of Sicily (GSA from 12 to 16; Recommendation GFCM/45/2022/5), Ionian Sea (GSA from 19 to 21; Recommendation GFCM/45/2022/6), and Levantine Sea (GSA from 24 to 27; Recommendation GFCM/45/2022/7). These MAPs, *inter alia*, establish to adopt a list of authorized vessels to fish in the each of above mentioned areas, and freeze the fishing capacity and effort of each countries authorized to fish at the levels of 2019. Furthermore, the MAPs fix a maximum catch by country for the transitional period 2023–2025, while waiting for countries to adjust their fishing effort and catch to a level compatible with MSY, which is the MAP target to be achieved by 2030. During the transitional period, countries involved in DWRS fisheries should identify VMEs and EFHs for juveniles and spawners of the species and verify any eventual overlap with the fishing footprint, adopting appropriate spatio-temporal conservation measures. In this regard, remote sensing systems for the control of fishing vessels (Vessel Monitoring System, VMS; Automatic Identification System, AIS; and Satellite-based synthetic Aperture Radar, SAR) provide the opportunity to apply "spatial" based measures of fishing effort management (Russo et al. 2014, 2019, D'Andrea et al. 2020), allowing selective protection of sensitive and critical deep-sea habitats, such as VMEs and EFHs. On the other hand, some researchers and environmental organizations have proposed closing bottom trawling permanently above a depth of 600 m, sustaining that the collateral ecological damage rises sharply beyond this depth, while the commercial yield per unit effort

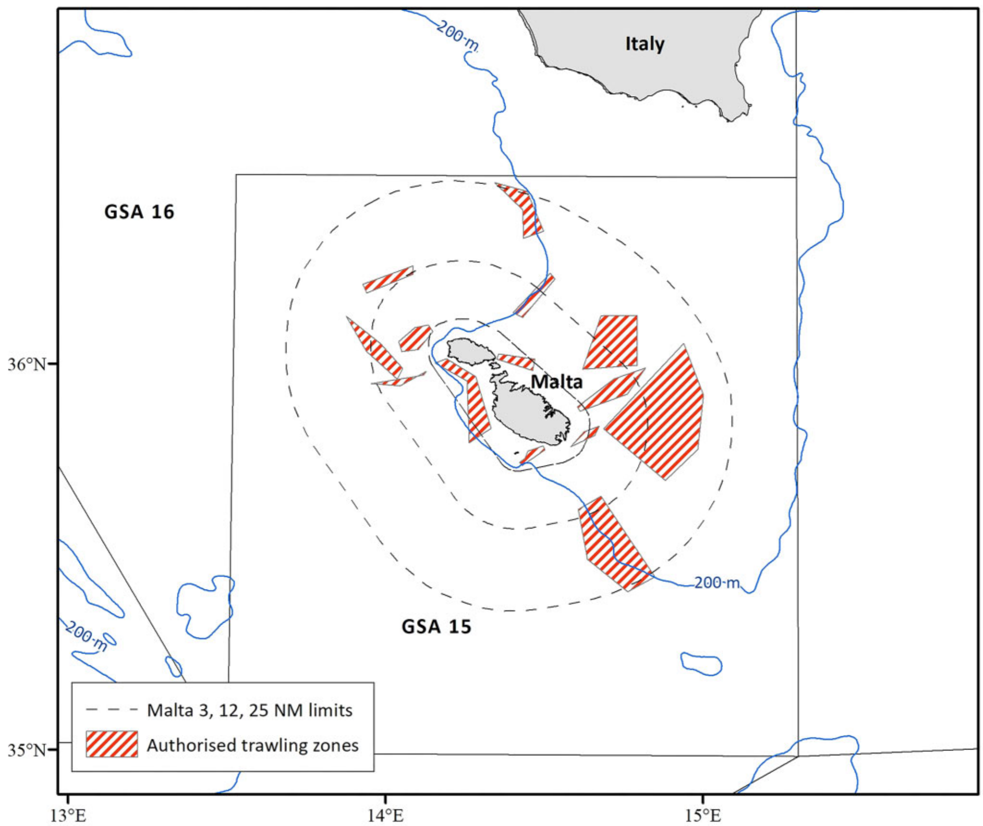

Figure 7. Map showing the areas where trawling is authorized within the Malta FMZ, as per Annex V of Council Regulation 1967/2006/EC (marked as "Authorized trawling zones"), trawling zones as amended trawling zones') (from Fisheries Management Plan—Fisheries Control Directorate, 2013).

diminishes (Clarke et al. 2015). While this proposal may be sound for conservation purposes, it is also evident that important fishing grounds for valuable crustaceans will be lost, causing economic damage to fisheries. This dilemma could find a more satisfying solution by adopting management strategies that are more complex than a "blanket closure." In other parts of the world, e.g. in the NEAFC or NAFO-managed areas (Thompson et al. 2016), deep-water fishing is allowed only on known fishing grounds. In fact, the exploitation of new areas is linked to the adoption of an "encounter protocol", which foresees the suspension of fishing activities in the presence of catches of VME indicator species. For example, in the northeast Atlantic, conditions for deep-sea fishing are regulated by Regulation (EU) 2016/2336, which prohibits bottom trawling between depths of 400 and 800 m, except within the existing fishing footprint. Furthermore, bottom trawling is not allowed in any closed areas that may be established to protect VMEs. In the Mediterranean, the only example of trawling allowed in well-defined spatial areas concerns the seabed within the Maltese Fishing Management Zone (MFMZ), which extends for 25 miles around the Maltese islands. These authorized trawlable areas were set by Annex V of Council Regulation (EC) 1967/2006 and subsequent amendments and additions within the MFMZ (Fig. 7). This spatially based fisheries management system is not specific to the DWRS fishery but is a general approach to regulating all fishing activities within the MFMZ. Its current implementation, supported by advanced track systems such as VMS and AIS, if properly enforced, limits trawling activities to designated fishing grounds, with the overall goal of avoiding impacts on other untrawled areas. This management approach, where fishing grounds alternate with protected areas, aims to balance the productivity of fishery resources with the protection of diversity of benthic communities and seabed across the entire area where the resources live. Understanding the connectivity between exploited and protected areas play a critical role in ensuring the long-term sustainability of marine ecosystems and need to be prioritized to facilitate the implementation of effective spatially based management systems. In addition, it is evident that, like any management system, effective control measures are necessary for spatially based regulation of fishing effort in order to avoid that the protection is only virtual and not real. Just as illustrative example, D'Onghia et al. (2017), using VMS proved that trawlers still often fish inside the FRA of Santa Maria di Leuca cold-water coral province with the aim of obtaining greater catches of DWRS and a greater number of large specimens of fish species, which find refuge in the coral area. Although evidence on the effectiveness of the Maltese System is somewhat limited, existing studies provide support for its adoption. Schembri et al. (2007) reported the presence of deep corals in areas not falling within the trawling lanes, highlighting the importance of preserving some nontrawling areas within the MFMZ. Dimech et al. (2009), based on interviews with key Maltese stakeholders, reported that the Maltese management system, centered on defined fishing areas and fleet capacity control, has been successful in enhancing resource abundance and reducing conflicts among different fishing sectors within the MFMZ. Additionally, Dimech et al. (2012), by comparing the abundance of DWRS in trawling and nontrawling areas within the MMFZ, inferred an active shift from nontrawling

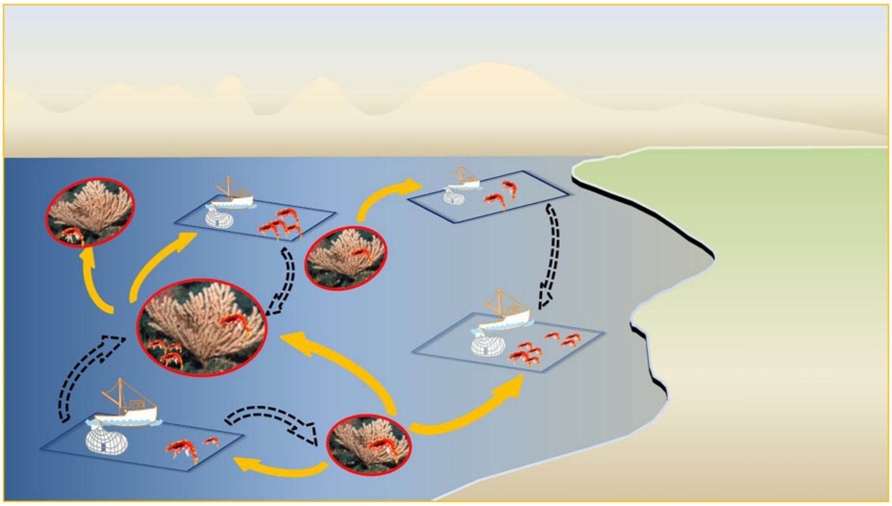

Figure 8. Diagrammatic representation of a spatial-based approach to fishery management in deep water habitats that are valuable for DWRS bottom trawling. Fishing grounds (rectangles) alternate with protected grounds that have high biodiversity (circles), and the arrows schematize possible DWRS connectivity between the exploited and protected areas.

areas and towards those where fishing is authorized. This shift, if properly managed in terms of fishing effort and catch, could be used for achieving a more sustainable fishery. In conclusion, the existing knowledge regarding the protection of EFHs and VMEs in mitigating the impacts of trawling on deep-sea ecosystems from diverse deep-sea areas of the Mediterranean, including studies by Maynou and Cartes (2012), D'Onghia et al. (2016, 2019), and Fanelli et al. (2017), provides ample evidence to support the spatially based approach to deep-sea fisheries management.

The fishing management system depicted in Fig. 8 is partly inspired by the Maltese model and is based on a spatial approach that alternates fishing areas with protected ones. The system is dynamic over time, requiring the fleet to move to another fishing ground when a minimum CPUE threshold (agreed upon among the fleets) is reached. Additionally, the search for new fishing grounds is guided by an "encounter protocol" that requires abandoning a fishing ground if vulnerable species are encountered.

Both the Ligurian fishery, with a long-term limited fishing capacity and activity, and the Mazara fleets in the Eastern Mediterranean, with a self-managed low number of boats per fishing ground, have proved the importance of controlling fishing effort on deep-water fishery resources to avoid reaching levels that compromise stock renewability. With the increasing number of deep-water trawler fleets in the Mediterranean, the need to regulate harvesting activities through a GFCM internationally agreed management plan has become more pressing.

Conclusions

The history of the examined DWRS fisheries in the central/eastern Mediterranean highlights the need for effective management strategies, emphasizing the challenges of managing a shared resource with fleets of different fishing capacities and socio-economic features. It is clear that, unmanaged deep-water fishing with high levels of capacity/effort can compromise the sustainability of fishing and the integrity of bottom habitats more than shallow waters fisheries. To limit the over-exploitation of Mediterranean DWRS, the GFCM adopted three MAPs in 2022 based on authorized fishing vessels and catch limits, regulated by the GFCM Data Collection Reference Framework (DCRF). Since DWRS fisheries are almost monospecific (other species such as large *M. merluccius* and *Phycis blennoides* make up only a small fraction of the catch), a management approach based on catch control rather than effort would be preferable (Pope 2009, Fiorentino and Vitale 2021). This option is further strengthened by the widespread incorporation of LED lights into trawl nets by the DWRS fleet in the Mediterranean, aiming to improve CPUE (Pinello et al. 2018, Geraci et al. 2021). This makes the expected relationship between fishing effort and fishing mortality, which is at the basis of a management regime relying on input control, weaker. In addition, it is evident that the sole adoption of classical management measures, such as fleet capacity control and catch quotas, is insufficient to reduce the harmful impacts of DWRS fisheries on benthic habitats and communities. To address this issue, it is necessary to ensure that fishing activities occur only in clearly identified fishing grounds that do not host VMEs. Similar to protocols implemented by other RFMOs (Thompson et al. 2016), and differently from the current approach of GFCM, vessels should adopt a protocol to move to other bottoms if species indicators of VMEs, such as *I. elongata*, are found while exploring previously unexploited fishing grounds. This approach could reduce the ecological impact on seabeds and benthic communities and contribute to maintaining a good status of bathyal ecosystems. Finally, to prevent the excessive depletion of local fish stocks, it might be beneficial to adopt a fishing ground rotation strategy based on CPUE thresholds, following the good practices of Mazara fishers. This involves moving from more exploited to less exploited fishing grounds, allowing depleted local abundances to recover while maintaining sustainable levels of fishing activity. These measures do not exclude the need for further work on new fishing gear to mitigate the impact of trawling on seafloor and resources.

Within this framework, it is crucial to emphasize the importance of a comprehensive monitoring of both the abundance and demography of the stocks at sea, as well as the catches and fishing effort of all the fleets targeting DWRS. This monitoring should be carried out across time and space, including not only the target species but also the noncommercial species associated with DWRS fisheries. By adopting such a holistic monitoring approach, the efficacy of the management measures in maintaining deep sea communities within relatively long-time sustainable conditions could be effectively assessed.

In conclusion, the management approach depicted in Fig. 8, based on a "mosaic" of areas for DWRS fishing alternating with no-trawl zones, could represent a promising path to balance production needs with conservation goals for the sustainable use of deep-sea renewable resources. This approach would serve three important purposes.

First, it recognizes that deep-water habitats are complex and interconnected systems, and that protection measures need to be implemented across the entire area where the resources live. By alternating fishing grounds with protected areas, this approach ensures that fishery resources can be sustainably harvested while minimizing the impact on benthic communities and seabed.

Second, the approach is adaptive and flexible. It allows for adjustments to be made to the size and location of both fished and/or protected areas based on new information and changing conditions. This is particularly important, given the potential impact of fishing activities. Vessels should relocate to other areas if vulnerable species are encountered, or if a minimum threshold of CPUE is reached, which could compromise the renewability of the resource.

Third, the approach should be collaborative and should involve stakeholders in the decision-making process. This fosters trust and support for management measures, paving the way for long-term sustainable fisheries that are comanaged through an adaptive model.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Author contributions

F.F.: conceptualization, methodology, investigation, writing—original draft, writing-review & editing. G.B.: conceptualization, methodology, investigation, writing-review & editing. G.G.: methodology, investigation, visualization, writing-review & editing. S.V.: conceptualization, methodology, investigation, writing-review & editing.

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