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The potential effects of COVID-19 lockdown and the following restrictions on the status of eight target stocks in the Adriatic Sea

Giuseppe Scarcella[1], Silvia Angelini[1,2], Enrico Nicola Armelloni[1,3*], Ilaria Costantini[1], Andrea De Felice[1], Stefano Guicciardi[1], Iole Leonori[1], Francesco Masnadi[1,3], Martina Scanu[1,3] and Gianpaolo Coro[4]

[1]Institute for Biological Resources and Marine Biotechnology (IRBIM), National Research Council of Italy (CNR), Ancona, Italy, [2]Fano Marine Center, The Inter-Institute Center for Research on Marine Biodiversity, Resources and Biotechnologies, Pesaro Urbino, Italy, [3]Department of Biological, Geological and Environmental Sciences (BiGeA), University of Bologna, Bologna, Italy, [4]Institute of Information Science and Technologies (ISTI), National Research Council of Italy (CNR), Pisa, Italy

The COVID-19 pandemic had major impacts on the seafood supply chain, also reducing fishing activity. It is worth asking if the fish stocks in the Mediterranean Sea, which in most cases have been in overfishing conditions for many years, may have benefitted from the reduction in the fishing pressure. The present work is the first attempt to make a quantitative evaluation of the fishing effort reduction due to the COVID-19 pandemic and, consequently, its impact on Mediterranean fish stocks, focusing on Adriatic Sea subareas. Eight commercially exploited target stocks (common sole, common cuttlefish, spottail mantis shrimp, European hake, red mullet, anchovy, sardine, and deepwater pink shrimp) were evaluated with a surplus production model, separately fitting the data for each stock until 2019 and until 2020. Results for the 2019 and 2020 models in terms of biomass and fishing mortality were statistically compared with a bootstrap resampling technique to assess their statistical difference. Most of the stocks showed a small but significant improvement in terms of both biomass at sea and reduction in fishing mortality, except cuttlefish and pink shrimp, which showed a reduction in biomass at sea and an increase in fishing mortality (only for common cuttlefish). After reviewing the potential co-occurrence of environmental and management-related factors, we concluded that only in the case of the common sole can an effective biomass improvement related to the pandemic restrictions be detected, because it is the target of the only fishing fleet whose activity remained far lower than expectations for the entire 2020.

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EDITED BY
Tomaso Fortibuoni,
Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Italy

REVIEWED BY
Pablo Del Monte-Luna,
Centro Interdisciplinario de Ciencias Marinas (IPN), Mexico
Juan Zwolinski,
University of California, Santa Cruz, United States

*CORRESPONDENCE
Enrico Nicola Armelloni
enrico.armelloni@irbim.cnr.it

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COVID-19, CMSY and BSM, Adriatic sea, stock assessment and management, fishing effort and co-management

Introduction

The COVID-19 global pandemic has forced many governments to temporarily shut down large segments of their economies to promote social distancing and reduce the infection rate, including businesses, restaurants, and schools (Althouse et al., 2020; White and Hébert-Dufresne, 2020; Hale et al., 2021). The unpredictable impacts of COVID-19 itself, and responses to it, were indeed felt throughout the food supply chains, including the seafood sector, at local and global scales (Bennett et al., 2020; FAO, 2020a; Love et al., 2021). Depending on the typology of the fishery, it is possible to detect a sort of gradient in the effect of COVID-19, going from a fishing effort reduction that was almost negligible (Coro et al., 2022c) to a complete shutdown of some fisheries (Pita et al., 2021).

In areas such as the Mediterranean Sea, where the status of the stock was considered for many years worrisome (Froese et al., 2018; FAO, 2020b), it is of great interest to understand whether the effects of the 2020 lockdown and the following restrictions in terms of social distancing have had any positive influence on the restocking of fishery resources. The present work aims to attempt an evaluation of the short-term effects of the pandemic-related exploitation pressure release on commercially exploited fish stock status. We focused on the most important target stocks of the Adriatic Sea, a subarea of the Mediterranean Sea (Geographical Sub-Areas 17 and 18; FAO, 1999) and one of the most exploited areas in the world in terms of trawling (Eigaard et al., 2017; Amoroso et al., 2018), with a high rate of productivity as well (Campanelli et al., 2011). The five countries bordering the Adriatic Sea and involved in fisheries, namely, Italy, Croatia, Slovenia, Albania, and Montenegro, all implemented several restrictions in 2020 due to COVID-19. In Italy, a lockdown period was imposed from March 11 to May 17. In almost the same period, Croatia, Slovenia, Albania, and Montenegro also adopted similar measures (Coro et al., 2022c). The restrictions in terms of social distancing affected the fishery sector, and a strong reduction in seafood requests caused a decrease in fishing pressure (Coro et al., 2022c) and related activities, such as fish markets (Pititto et al., 2021). As soon as the harsh restrictions were loosened, fishing intensity in the Adriatic Sea quickly reverted to pre-COVID levels for the majority of the fleet categories (Russo et al., 2021; Russo et al., 2022; Coro et al., 2022c).

COVID-related restrictions in the Adriatic Sea need to be examined within a fishery system where factors such as environmental conditions and management measures can be seen as major forces acting on the stock dynamics (Coll et al., 2009; Fortibuoni et al., 2017). Therefore, we ought to make some assumptions to try to disentangle these factors. Concerning environmental conditions, the climate change effect in this area has been documented for many years (Ben Rais Lasram et al., 2010; Fortibuoni et al., 2015). Considering the inertia underlining these processes, we can assume that the environmental drivers observed in 2020 trace a continuum with 2019. Regarding the effect of management, the major instruments in place for 2020 were the multiannual management plan for the sustainable demersal fisheries in the Adriatic Sea (GFCM/43/2019/5), the management plan for the sustainable small pelagic (anchovy and sardine) fisheries in the Adriatic Sea (last update GFCM/42/2018/8), and the recommendation defining the Pomo/Jabuka pits as a Fishery Restricted Area (FRA; GFCM/41/2017/3). Among these measures, only GFCM/43/2019/5 was deemed to start in 2020, while other recommendations were already put in place in previous years. Due to the lack of responsiveness of the management system in the Mediterranean Sea (Cardinale et al., 2017), the measures that were decided before the start of the global pandemic were applied without any change: for example, the reduction in fishing days foreseen in management plans on demersal or small pelagic stocks was applied in 2020. Therefore, in some cases the pandemic-related restrictions added up to the fishing ban foreseen by the management plan.

Before discussing any potential effect of the pandemic restrictions, there is the need to quantify the effective fishing pressure reduction attributable to the anti-COVID measures and determine which fleets are mostly affected. To account for interactions with management measures already in place, we accompany a description of the fishing effort alterations between 2019 and 2020 with a brief review of the ongoing management actions, trying to distinguish the fishing activity reduction due to management from those due to the pandemic. We then proceed to quantify the potential reduction in fishing mortality and the potential increase in biomass at sea of the most important target stocks exploited by Adriatic fleets, namely, six demersal and two small pelagic stocks routinely assessed within the General Fishery Commission for the Mediterranean (GFCM) and the

Scientific, Technical and Economic Committee for Fisheries of the European Commission (STECF). We conclude by discussing the merits of a management system based on fishing effort reduction, especially when using fishing days as a unit of measure.

Material and methods

Fishing effort alteration

Effort data in terms of fishing days and hours at sea are available for European fleets from the STECF FDI 2021 data call (STECF, 2021a); fishing hours from AIS data processing are available from a regional study (Coro et al., 2022c) and were used for comparison. In the FDI dataset, data for pots, nets, and longlines were grouped under the "Passive" category; data for Croatian Dredges were grouped with Italian beam trawlers (Armelloni et al., 2021). The resulting information was aggregated by quarter and the effort change calculated by dividing the value shown in 2020 by the value shown in 2019.

Target stocks and associated data

The demersal and small pelagic stocks considered in the present study are the following: common sole (*Solea solea*), common cuttlefish (*Sepia officinalis*), and spottail mantis shrimp (*Squilla mantis*) in Geographical Subarea (GSA) 17, that is, the North and Central Adriatic Sea; European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), anchovy (*Engraulis encrasicolus*), and sardine (*Sardina pilchardus*) in GSAs 17-18, which include the whole Adriatic basin (North, Central, and South Adriatic Sea); and deepwater pink shrimp (*Parapenaeus longirostris*) in GSAs 17–18–19, corresponding to the entire Adriatic Sea and the Western Ionian Sea. In the 2015–2020 period, the listed stocks represented on average almost 70% and 50%, respectively, in landing weight (tonnes) and value (euros) of the entire commercial fishing activity of EU fleets working in GSAs 17 and 18 over the last 5 years (source: STECF, 2020a). Moreover, the species are the main target of important fleets operating in the area as bottom otter trawlers (OTB), bottom beam trawlers (TBB), pelagic pair trawlers (PTM), purse seiners (PS), and small-scale fishery using passive gears (PGP). In addition, they are also subject to yearly stock assessments carried out within the framework of both STECF and GFCM working groups. Different sources were used to reconstruct fishery-dependent and -independent time series to be used in the following model. Data for demersal species were gathered from STECF FDI (STECF, 2021a), STECF stock assessment, GFCM stock assessment reports (FAO, 2021a; FAO, 2021b; FAO, 2022a), and GFCM stock assessment forms (SAFs updated to the reference year 2019 at the time of writing; available at https://www.fao.org/gfcm/data/safs/zh/); catch data for small-pelagic species were extracted from the graphs contained in FAO (2022b), and fishery-independent data for small pelagic species were provided by CNR-IRBIM. Stock assessment models used in the official stock assessments are Stock Synthesis 3 (SS3, Methot and Wetzel, 2013), assessment 4 all (a4a, Jardim et al., 2014), CMSY (Froese et al., 2017), and the FLR implementation of the SAM method (FLSAM, Payne and Hintzen, 2013) (details by species are reported in Table 1).

TABLE 1 Summary of the stocks analysed in the present paper, with references to the FAO 3 alpha code, the assessment method used in the official context, the geographical aggregation (GSAs), and data and priors used in the CMSY analysis.

Stock	FAO 3 alpha code	Official Stock Assessment method	GSAs	Start year	*r* range	Biomass start	Biomass int. yr	Biomass int	Biomass end
Engraulis encrasicolus	ANE	FLSAM	17-18	2000	0.39-0.91	0.01-0.4	NA	NA	0.01-0.4
Merluccius	HKE	SS3	17-18	1998	0.35-0.8	0.01-0.4	NA	NA	0.01-0.4
Mullus barbatus	MUT	A4a	17-18	2006	0.42-1.04	0.01-0.4	NA	NA	0.01-0.4
Parapenaeus longirostris	DPS	A4a	17-18-19	2002	0.68-1.54	0.01-0.4	NA	NA	0.2-0.6
Sardina pilchardus	PIL	FLSAM	17-18	2000	0.4-0.9	0.01-0.4	NA	NA	0.01-0.4
Sepia officinalis	CTC	CMSY	17	1974	0.37-0.84	0.4-0.8	2007	0.1-0.5	0.05-0.4
Solea solea	SOL	SS3	17	1958	0.33-0.76	0.4-0.8	NA	NA	0.01-0.4
Squilla mantis	MTS	SS3	17	1953	0.37-0.84	0.2-0.6	NA	NA	0.01-0.4

The reference year for all the assessments was 2020. NA, not assigned.

CMSY model

The stock assessment of the selected stocks was performed using the CMSY model (Froese et al., 2017). CMSY includes a Bayesian Schaefer model (BSM), which fits catch and—optionally—biomass (or catch-per-unit-of-effort) data through a Markov chain Monte Carlo method based on the Schaefer function for biomass dynamics. The model estimates fisheries reference points (MSY, F_{MSY}, B_{MSY}), as well as relative stock size (B/B_{MSY}) and exploitation (F/F_{MSY}) from catch data and broad priors for "resilience" (approximated by r) and stock's relative biomass (B/k) at the beginning and end of the catch time series. For the purposes of this paper, BSM was applied on landing data and biomass indices. Table 1 summarizes the input data and priors used for each stock. Catch data for all species were derived from published stock assessment working group reports (see the previous section). The biomass indices for common sole, common cuttlefish, and spottail mantis shrimp in GSA 17 were obtained from the SoleMon project (Grati et al., 2013), a trawl survey carried out from 2005 up to present times with Rapido trawl (Hall-Spencer et al., 1999) over a 36,742-km^2 area of the Northern and Central Adriatic Sea (Scarcella et al., 2014). In 2020, no SoleMon survey was carried out in the area comprised between the midline and Croatian waters, and missing hauls were provided by model-based estimates (Coro et al., 2022a). The biomass indices for European anchovy and sardine in GSAs 17–18 were obtained from the MEDiterranean International Acoustic Survey (MEDIAS; Leonori et al., 2021). MEDIAS surveys were carried out in the European Mediterranean Sea following a standardised protocol to provide inputs for the management of small pelagic fish. MEDIAS data used in this paper are in tonnes by NM^2 obtained from the survey conducted in the western Adriatic Sea (Italian and Slovenian water), where the acoustic survey has been performed since 1976. The biomass indices for European hake and red mullet in GSAs 17–18 and deep-water rose shrimp in GSAs 17–18–19 were collected from open-source stock assessment reports (STECF, 2021b), which include the annual biomass at sea values estimated from the International Bottom Trawl Survey in the Mediterranean Sea (MEDITS; Anonymous, 2017; Spedicato et al., 2019). The MEDITS is a European survey which started in 1994 in order to collect data and information about the demersal communities inhabiting the Mediterranean basin. Priors for r were either taken from previous specific studies in this area (Froese et al., 2018; Armelloni et al., 2021) or inferred from their averages in FishBase and SeaLifeBase (Palomares and Pauly, 2018; Froese and Pauly, 2019). The choice of an increasing pattern from the initial to final depletion priors in the reference models was supported by an overall increase in fishing pressure in the Adriatic Sea (Colloca et al., 2017) followed by a reduction in the productivity of the commercial fishery over the study period (Marini et al., 2017). Moreover, the assessment results available from official stock assessment reports and GFCM SAF reports 2020 were also used to infer the depletion priors. The CMSY-BSM models were employed with time series until 2019 (before COVID-19) and until 2020 (during COVID-19). The results were compared to understand the impact of the COVID pandemic using the ratio of F_{2020}/F_{2019} and B_{2020}/B_{2019}. An overview of the official stock assessment results for 2019 and 2020 is provided for completeness (Table 1).

Statistical comparisons of the CMSY outputs

The statistical comparisons between 2019 and 2020 F/F_{MSY} and B/B_{MSY} data were carried out using bootstrap (Efron and Tibshirani, 1993). For each species and each variable of interest, the difference in medians between the years 2020 and 2019 was tested as follows (Efron and Hastie, 2016). Raw data were the 6,000 point estimates for B/B_{MSY} and F/F_{MSY} coming from the JAGS implementation in the CMSY model, which are the data already providing the CMSY results. Starting from the raw data, for each species, 10,000 replicates with replacements for both 2020 and 2019 were carried out. From these replicates, 10,000 values of the difference between 2020 and 2019 medians were derived. On this set of 10,000 differences, the mean and the relative 95% CI were then calculated. If the 95% CI did not capture the zero value, the difference was deemed statistically significant. All the calculations were carried out using the free statistical software R (R Core Team, 2022).

Results

In the present section, comparisons between 2020 and 2019 fishery-dependent and -independent data were carried out. A similar comparison was carried out on the CMSY/BSM outputs as well.

Fishing effort alteration

When commenting on the results, it must be considered that some differences between AIS data and FDI data can be imputed to the following factors: (i) AIS gear categorization is model-based (Galdelli et al., 2021), while FDI data are assigned to fishing gear based on official registers (EU, 2020); (ii) AIS data do not include small vessels (smaller than 15 m of LFT) that are not equipped with AIS transponder; non-EU fleets (Albania and Montenegro) are included only in the AIS data. The comparison of 2020 *vs.* 2019 reduction among fishing days, hours at sea (from FDI data), and fishing hours (from AIS data) did not yield a coherent picture of the fleets considered (Figure 1), since in

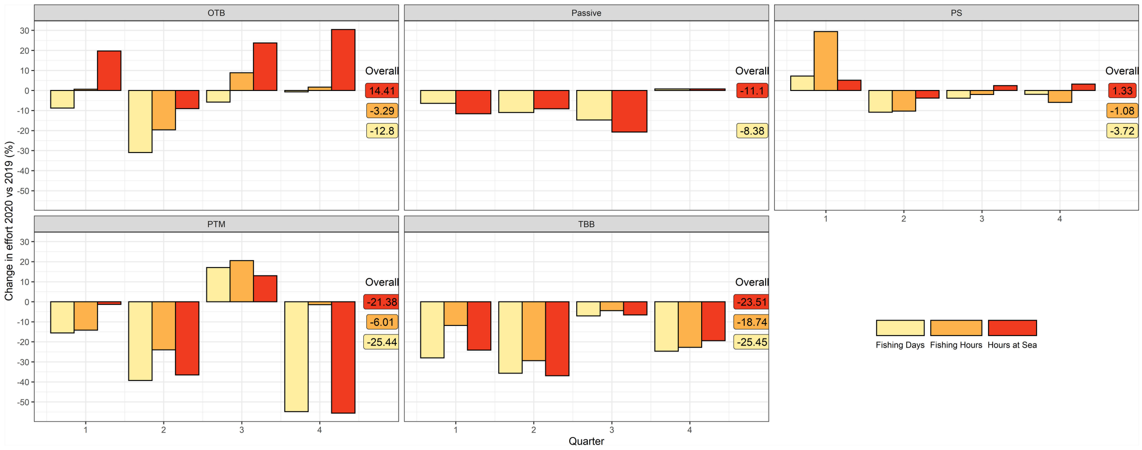

FIGURE 1
Seasonal change in fishing effort in the period 2019–2020 in the Adriatic Sea (GFCM-GSAs 17 and 18). Fishing days and hours at sea are derived from FDI data (STECF, 2021a) fishing hours from AIS data taken from Coro et al., 2022c. Metièrs are otter bottom trawlers (OTB), purse seiners (PS), pelagic midwater trawlers (PTM), and beam bottom trawlers (TBB). TBB comprises dredgers (DRB) from Croatia that are using beam trawl. Passive gears include the following gears: FPO, FYK, GND, GNS, GTN, GTR, HMD, LHM, LHP, LLD, LLS, LTL; Other include the following gears: OTM, NK, SB, SV. Acronyms full list available at https://datacollection.jrc.ec.europa.eu/wordef/gear.

most of the cases the magnitude of the difference observed between 2019 and 2020 depends on the indicator selected. Fishing activity metrics agreed on a reduction in Bottom trawlers (OTB) activity only in the second quarter of 2020. In detail, during the first quarter an increase was observed in fishing activity when focusing on hours at sea not confirmed by other metrics (barely any change in fishing hours and a decrease in fishing days). In the second quarter, a marked reduction was observed in fishing days (as much as -30% in the second quarter), corresponding to a less marked reduction in fishing hours (-20%) and a slight decrease in hours at sea (-10%). In the third quarter, fishing days were indicating a slight reduction (-6%), while fishing hours (+ 9%) and hours at sea (+24%) suggested that the activity was higher than pre-COVID levels. In the fourth quarter, hours at sea indicated a steep increase while the other indicator suggested a fishing activity very similar to the previous year. Passive gears (not available from AIS data) showed a slight activity reduction in both fishing days and hours at sea for quarters 1–3, with the third quarter showing the most severe reduction. The fourth quarter registered a negligible variation vis-à-vis the year 2019. Purse seiners (PS) showed a less marked variation in terms of fishing activity; namely, a sudden increase in fishing hours was observed in the first quarter (not confirmed by the other metrics), followed by a moderate reduction in the second quarter, not exceeding 10%, as confirmed by all indicators. In the rest of the year, the activity variation remained almost negligible, generally comprised within ±6%. Pelagic pair trawlers (PTM) experienced a strong activity reduction already in the first quarter (not confirmed by the hours at sea). In the second quarter, indicators confirmed a strong reduction, exceeding -20% at least. The fishing activity reverted to a value higher than the pre-COVID period in the third quarter, with an increase of 10%–20% (depending on the indicator). During the fourth quarter, the FDI indicators reported a fishing activity drop of over 50%, while the AIS data suggested values comparable to 2019. Beam trawlers (TBB) were the only fleet showing decreasing values in all quarters, regardless of the indicator considered. During the first quarter, a moderate decrease was observed in each indicator, with values comprised between -10% and -28%. In the second quarter, a marked reduction, around -30% on average, was discernible. In the third quarter, the fishing activity recovered but remained slightly below the previous year levels. In the fourth quarter, the fishing activity dipped again, with a reduction of close to -20% confirmed by all indicators.

Target stocks and associated data

According to FDI statistics and data available from stock assessment reports, a clear increase of catches (C) in 2020, around 15%, has been observed only for European hake, unlike the remaining stocks that showed a decrease in catches, more evident for demersal species such as common cuttlefish, red mullet, and common sole. The biomass indexes (I) available from bottom trawl surveys (SoleMon and MEDITS) and an acoustic survey (MEDIAS) showed a notable reduction for deepwater pink shrimp and common cuttlefish, approximately

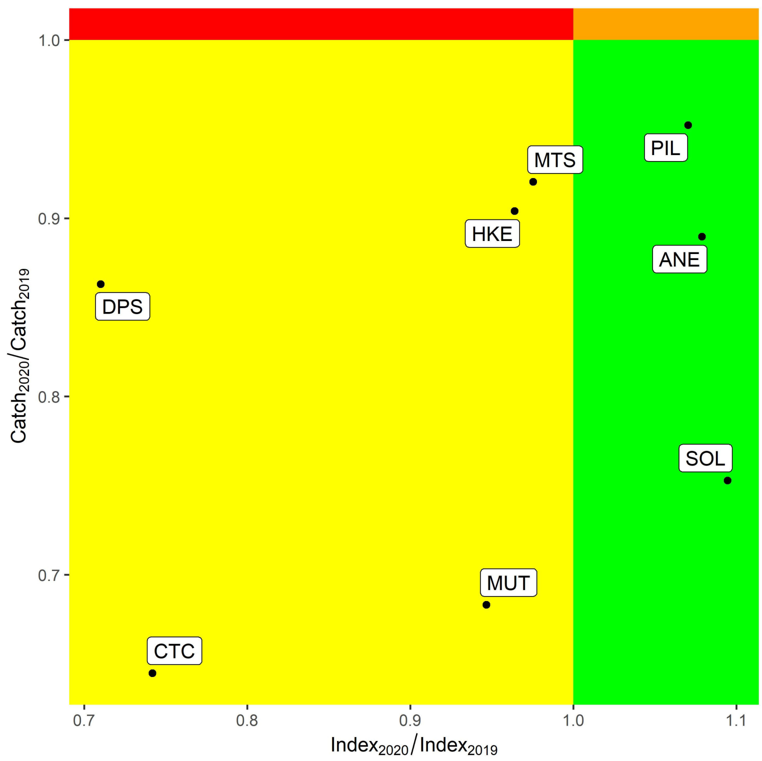

FIGURE 2
Kobe plot with ratio of catches (C) and biomass indexes (I) in 2020 and 2019 of the eight Adriatic Sea target stocks.

TABLE 2 Results of the official stock assessment models and from the CMSY models.

Stock	Stock assessment	F/F_{ref} 2019	F/F_{ref} 2020	F/F_{ref} 2020 *vs.* F/F_{ref} 2019	B/B_{ref} 2019	B/B_{ref} 2020	B/B_{ref} 2020 *vs.* B/B_{ref} 2019
Engraulis encrasicolus	Official	1.51	1.15	0.762	0.422	0.49	1.161
	CMSY	1.833	1.252	0.683	0.8	1.1	1.375
Merluccius merluccius	Official	2.72	2.47	0.908	1.56	1.62	1.038
	CMSY	0.819	0.735	0.897	0.823	0.84	1.021
Mullus barbatus	Official	2.029	1.028	0.506	8306*	10411*	1.253
	CMSY	0.931	0.69	0.74	0.864	0.872	1.01
Parapenaeus longirostris	Official	2.98	2.256	0.757	3245.5*	3246.833*	1
	CMSY	1.093	1.086	0.994	1.078	0.973	0.903
Sardina pilchardus	Official	4.43	NA	NA	0.67	NA	NA
	CMSY	2.111	1.938	0.918	0.535	0.549	1.027
Sepia officinalis	Official	0.81	1.17	1.444	0.49	0.36	0.735
	CMSY	1.096	1.171	1.068	0.417	0.363	0.871
Solea solea	Official	1.125	0.81	0.72	0.69	0.73	1.058
	CMSY	1.202	0.997	0.829	0.893	0.911	1.02
Squilla mantis	Official	0.917	0.79	0.862	0.74	0.92	1.243
	CMSY	1.013	0.874	0.863	0.797	0.807	1.013

For the official models, 2019 sources for Sepia officinalis, Merluccius merluccius, Squilla mantis is (FAO, 2021a), common sole in 2019 (FAO, 2021b), Parapenaeus longirostris and Mullus barbatus (STECF, 2020b), Engraulis encrasicolus and Sardina pilchardus (FAO, 2021c) and 2020 for Sepia officinalis, Merluccius merluccius, Squilla mantis and common sole (FAO, 2022a), Parapenaeus longirostris and Mullus barbatus (STECF, 2021b), Engraulis encrasicolus, and Sardina pilchardus (FAO, 2022b). *Unit of measure is SSB; NA, not available. Fref and Bref correspond to the estimated F_{MSY} and B_{MSY} values for the stock assessment developed with CMSY, whereas Fref and Bref for the official stock assessments agree with those officially selected and set out in the reports cited above.

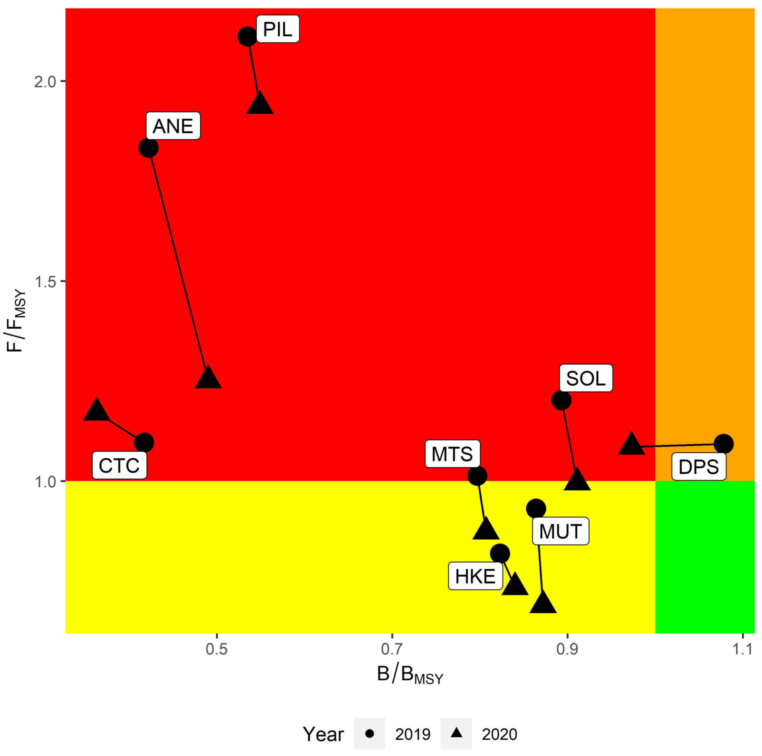

FIGURE 3
Kobe plot showing the outputs of CMSY/BSM of eight Adriatic Sea target stocks in 2019 (triangle) and 2020 (circle). Lines link the outputs for the same species in different years.

30%, while the remaining stocks showed a stable trend from 2019 to 2020, with a moderate increase for small pelagic species and common sole (Figure 2).

CMSY model

The results of the stock assessment model used to investigate the status of the eight Adriatic Sea target stocks (Table 2 and Figure 3) revealed that both in 2019 and in 2020, most of the stocks were in overfishing ($F_{current}$ higher than F_{MSY}) and overfished ($B_{current}$ lower than B_{MSY}) conditions. Stock trajectories for B/B_{MSY} and F/F_{MSY} for the CMSY models having as reference year 2019 and 2020, respectively, are available in the Supplementary Information (Figures SI 2, 3). Common cuttlefish, anchovy, sardine, and hake proved to be in overfishing and overfished conditions in both years considered. Common sole and spottail mantis shrimp showed an improvement in terms of reduction in fishing mortality, which was below the F_{MSY} in 2020. Deepwater pink shrimp was in overfishing conditions in 2019 only and in both overfishing and overfished conditions in 2020. Red mullet stock showed a current F below F_{MSY} in both 2019 and 2020. All the stock assessment outputs showed wide ranges of uncertainty. All the CMSY model outputs and diagnostics are available in the Supplementary Information (Figures SI 4 to 83). The direction of the difference (whether positive or negative) between results for 2019 and 2020 is coherent between the estimates of the present paper and the official stock assessment, except for deepwater rose shrimp biomass that was stable in the official stock assessment and slightly decreasing in this paper.

Statistical comparison of the CMSY outputs

CMSY point estimation for the reference years 2019 and 2020 is available in the Supplementary Information, Figure SI 1. Looking at the comparative plot in Figure 4 and Tables 2, 3, it is possible to detect a small but significant improvement in stock conditions for most of the stocks in terms of both biomass at sea and reduction in fishing mortality. The countertrend stocks were common cuttlefish and deepwater pink shrimp, which showed a reduction in biomass at sea and, only for common cuttlefish, an increase in fishing mortality. The only non-significant

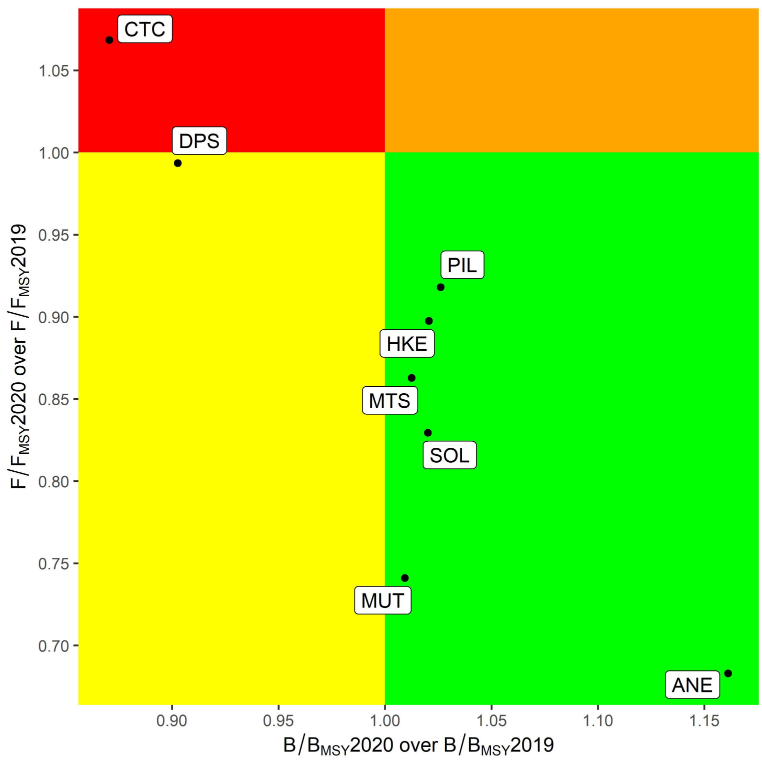

FIGURE 4
Comparative Kobe plot showing the 2020/2019 ratio of the F/F_{MSY} and B/B_{MSY} outputs from the CMSY/BSM outputs of eight Adriatic Sea Target stocks.

differences were observed for deep-water pink shrimp in respect of fishing mortality.

Discussion

According to our knowledge, the present study is the first attempt to quantify the status of target stocks concerning the 2020 COVID-19 lockdown and related restrictions that occurred in the countries exploiting the resources in the entire Adriatic Sea. It is important to stress that pre-crisis fisheries evaluations which showed that the situation of several of our target stocks was already worrying, in agreement with historical data and recent studies (Colloca et al., 2017; Fortibuoni et al., 2017; Armelloni et al., 2021).

TABLE 3 Mean and 95% confidence intervals of the B/B_{MSY} and F/F_{MSY} differences in medians between 2020 and 2019 calculated by bootstrap as a function of species.

Stock	Area	B/B_{MSY}	LCI	UCI	Sign.	F/F_{MSY}	LCI	UCI	Sign.
Engraulis encrasicolus	17,18	0.068	0.060	0.076	*	0.579	0.521	0.631	*
Merluccius merluccius	17,18	0.017	0.014	0.021	*	0.084	0.078	0.091	*
*Mullus barbatus**	17,18	0.009	0.004	0.014	*	0.242	0.233	0.251	*
*Parapenaeus longirostris**	17,18,19	-0.105	-0.112	-0.097	*	0.006	-0.007	0.019	
Sardina pilchardus	17,18	0.015	0.008	0.021	*	0.174	0.139	0.209	*
Sepia officinalis	17	-0.054	-0.060	-0.049	*	-0.075	-0.106	-0.044	*
Solea solea	17	0.017	0.013	0.021	*	0.206	0.195	0.217	*
Squilla mantis	17	0.01	0.004	0.016	*	0.138	0.127	0.149	*

LCI and UCI represent the lower and upper 95% confidence interval limit, respectively. A difference is considered statistically significant when its confidence interval does not include 0. In the table, these differences are highlighted in bold and marked with the * symbol in the "Sign." Column.

Management of target stocks and COVID-related effects on fishing

The review of fishing effort data done in the present paper highlights that all major commercial fleets fishing in the Adriatic Sea reduced their activity during the months when severe COVID-19 restrictions were in place. When the social limitations were relaxed, the fishing fleets responded in a heterogeneous way: some fisheries were unable to fully recover to pre-COVID rates, while others increased their activity to levels higher than in 2019. The multiannual management plan for the sustainable exploitation of demersal stocks in the Adriatic Sea adopted in 2019 (GFCM/43/2019/5) required a substantial fishing effort reduction for the 2020–2021 period to foster stock rebuilding. In particular, in 2020 it established a 12% fishing-day reduction for OTB and a 16% fishing-day reduction for TBB, compared to their average values for the 2015–2018 period. Based on 2021 FDI data, on a subset considering European fleets in GSAs 17 and 18, the fishing-day values observed in 2020 suggest that the effort reduction was in line with the expectation for OTB (-12.8%) and far higher for TBB (-25.4%). However, when fishing hours are used as an indicator, the change in fishing effort drops to just -3.3% for OTB and to -18.7% for TBB. Seasonal fishing data give us more detail on the topic. OTB experienced a sharp activity reduction in spring (detected by all the indicators) followed by a quick recovery, and activity in summer/fall was comparable to or even higher than the previous year depending on the indicator. Therefore, the effect of COVID-19 restrictions on OTB mostly concentrated on the fishing-day reduction foreseen by the management plan within the spring period, and the dynamics observed in the second half of 2020 suggests a reframing of the fishing activity instead of an effective fishing pressure reduction. On the contrary, all indicators agree on depicting TBB activity in 2020 at levels lower than 2019 for the entire year, in any case describing a more severe reduction than the management plan claims. As a consequence, there is evidence that the pandemic restriction effectively forced TBB activity to be far lower than expectations. Another management aspect for demersal fisheries that might have interacted with COVID restrictions is GFCM/41/2017/3, which defines a Fishery Restricted Area (FRA) in the Pomo/Jabuka pit, a heavy exploited and productive area. The Pomo FRA is deemed to protect essential fish habitat for European hake and Norway lobster, with the first experiencing a positive biomass trend over recent years (Chiarini et al., 2022). Considering that the effective fishing effort reduction in the Pomo area was limited to a few weeks (FAO, 2021d) and that this area is not fished by TBB (Armelloni et al., 2021; Coro et al., 2022c), we assume a negligible interaction of this management measure with COVID-related restrictions.

The management plan for the sustainable exploitation of small pelagic (anchovy and sardine) stocks in the Adriatic Sea was adopted in 2013 (GFCM/37/2013/1). After several updates, the latter regulation (GFCM/42/2018/8) recommends for 2019–2021 a limitation of fishing days equal to 180 per year (not exceeding 144 days targeting a single species) and a reduction in catches of 5% year after year. In addition, seasonal closures of 30 continuous days within the period 1 October–31 March for sardine and 1 April–30 September for anchovy are foreseen; these fishing bans are differentiated by country, region, and fishing gear (purse seine and pelagic trawl). The only fishing ban falling within the lockdown period was the one for Italian purse seiners targeting sardine, which was planned for the period 20 February–21 March 2020. All the other fishing bans were planned in different periods and did not overlap with the most severe COVID restrictions. Therefore, if the management plan was not imposing a fishing effort reduction from 2019 to 2020, based on the interaction between management recommendations and COVID restrictions, it is reasonable to expect a slight reduction in fishing activity for the gears targeting small pelagic species, especially for PTM, because of the cumulative effect of COVID restrictions and the planned fishing ban. When looking at the data, PS activity was almost unchanged, while a marked drop is detected in PTM fishing days (although fishing hours indicate a less severe reduction). Seasonal data confirm that PS activity remained quite stable throughout the year, experiencing a less severe contraction during the 2020 spring among the analysed fleets. As a consequence, there is no evidence that the pandemic restrictions caused an effective reduction in PS activity. PTM activity underwent a strong reduction during the lockdown period, then the fishery quickly recovered in summer according to all indicators. The discrepancy observed among the indicators for PTM in fall complicates the interpretation of data, because it may either indicate a dramatic reframing of the fishing practice or a bias in the fishing data model estimate. However, when looking at FDI data, including years from 2014, what emerges is a slight but continuous contraction of PTM activity over the last 5 years. Therefore, for PTM there are indications that the pandemic restrictions added up as an extra driver of fishing effort reduction to a fleet segment already experiencing a gradual contraction.

Environmental drivers

Environmental drivers that could influence a population increase in 2020 were scarcely effective for common sole, since its habitat distribution is not sensible enough to the magnitude of alteration of chlorophyll, dissolved oxygen, and temperature that occurred in 2020 compared to the previous years (Coro et al., 2022b). Environmental change was also unlikely to be strong enough to change the habitat distribution of spottail mantis shrimp and anchovy. However, temperature increase and dissolved oxygen decrease in 2020—which were climate change-related trends—might have fostered the habitat distribution of common cuttlefish and penalised that of pink shrimp with a resultant influence on biomass. Habitat unsuitability might indeed be one additional reason for the particular condition of deepwater pink shrimp shown in Figure 4. Instead, COVID-specific environmental changes, like chlorophyll-a decrease, slightly penalised sardine (Coro et al., 2022b). A substantial water-column chlorophyll-a decrease from 2019 to 2020 was indeed measured in the Adriatic and was likely a consequence of the COVID-19 pandemic. This reduction was observed worldwide and potentially corresponded to CO_2 emission dropping in several areas as a result of human activity reduction (Coro et al., 2022b). One logical explanation is that chlorophyll-a is an integral part of the carbon cycle, because this cycle strongly depends on CO_2 consumption during photosynthesis. Thus, in the global balance of the natural carbon cycle, a significant CO_2 decrease likely corresponds to a chlorophyll-a level decrease because of the lower demand for CO_2 uptake. When coupled with temperature increase, a lower chlorophyll-a creates new environmental conditions that may influence species' presence and abundance (Coro et al., 2022a).

Comparison between CMSY/BSM outputs and official assessments both in 2019 and in 2020

Most of the stocks analysed in the present work are routinely assessed, generally with age-based models, in the framework of the Scientific Advisory Committee (SAC) of the GFCM. We acknowledge that in this work we applied a surplus production model (SPM) to every stock, a methodology that is sometimes defined as too simplistic to account for the variability of size structure, ecological drivers, and catchability of a real-world stock (Pedersen and Berg, 2017). Nevertheless, modern SPMs greatly improved on these caveats by modulating the error component, thereby improving the model parameter estimation, and nowadays these models are widely used in the official stock assessment context as well. Since the purpose of this paper is not to revise the stock assessment methodology in the Adriatic Sea but to assess whether COVID-19-related restrictions have in some way affected the stock status, we preferred to adopt a common methodology for all stocks. In this case, an SPM such as CMSY was the best candidate because of its flexibility, ease of use, and successful applications to a variety of stocks worldwide (Froese et al., 2018; Palomares et al., 2020). Nevertheless, to verify consistency with the official stock assessment, before commenting on the possible effect of COVID-19 restrictions on the stocks, we provide a brief qualitative comparison of the results obtained in the present work and official stock assessments (STECF, 2020c; FAO, 2021a; FAO, 2021b; STECF, 2021b; FAO, 2021c; FAO, 2022a; FAO, 2022b). In the SI, all the CMSY model outputs (Figures SI 4 to 83) are included, to allow the reader to carry out a detailed comparison with the results provided in the official stock assessment reports.

Regarding demersal species, the situation of hake depicted by the official stock assessment differs from the one described by the CMSY model. F results are below the reference values for both years in the CMSY model, describing a downward trend from 2019 to 2020; this reduction is also depicted by the official stock assessment, estimating however a value of F above the respective reference points. SSB increases from 2019 to 2020, as underlined by all the assessments; however, the official stock assessments depict a more positive situation in which SSB is above the reference points for 2019 and 2020 alike, whereas the biomass is below B_{MSY} for the CMSY models. One of the main reasons for these contrasting results is the fact that CMSY and the official stock assessment carried out in SS3 are very difficult to compare (Bouch et al., 2020). The main source of information for the CMSY model consists in the catch amount and the survey index, whereas SS3 also considers the population's structure of the target stock, as well as different biological features. In addition, SS3 includes a wide number of parameters related to catchability and other aspects (Methot and Wetzel, 2013). However, if SS3 is considered the best model for assessing the hake stock in Adriatic waters (FAO, 2020a), the CMSY model proves valid for the aim of this study, and they substantially agree on a significant reduction in fishing mortality in the last year. For common sole, this study and the official benchmark assessment substantially agree on a significant reduction in fishing mortality in the last year: the state of the Adriatic stock in 2019 was one of overfishing with low biomass, while the result for 2020 reflects the sharp drop in fishing mortality with a value below the reference point in the last year. The stock status of spottail mantis shrimp in GSA 17 in the GFCM context showed in 2019 and 2020 the same trend resulting from the analysis conducted through the CMSY model: a moderate reduction in fishing mortality mirrored by an increase in biomass. The status of spottail mantis shrimp slightly differs only in the final classification to the reference point: indeed, it was in the yellow area of the Kobe plot in 2019 and 2020 GFCM results, while it moved from the red to the yellow area in the same CMSY outputs. For cuttlefish in GSA 17, the configuration in the GFCM context was revised from 2019 to 2020 by changing crucial prior information, compromising any possible comparison with the results of this work. The parameters of the most recent assessment were adopted here. Biomass trajectory decreased from 1980 to 2010 when it dropped below 0.5 B/B_{MSY}. In recent years, the poor biomass status had some minor oscillation but remained quite stable, with a slight decrease from 2019 to 2020. Fishing mortality extensively fluctuated along the time series, and it is generally declining, but the model having 2020 as the reference year estimated an increase compared to 2019. The deepwater pink shrimp official assessments show a biomass trajectory increase from 2012, which stabilizes in 2019 and 2020. F trajectories, albeit with some minor oscillation, remained barely constant from 2012 to 2019, indicating an overfishing status for 2019 and 2020, with a slight increase in fishing mortality in the last year. The CMSY model also captured the large biomass increase from 2012, although it estimated a slight decrease in recent years. The F trajectories of the CMSY model were in a flux but stabilised in recent years, indicating a moderate increase of the F from 2019 to 2020 in line with the official assessment. For red mullet, the available official assessments describe an upward biomass trajectory from 2010, with a sudden increase in 2018. F trajectories are mirroring the biomass and were halved from 2018 to 2020, switching from an overfishing status for 2019 to a condition of F in line with the reference point for 2020. In the present paper, the CMSY estimated a biomass trajectory similar to the official assessment but much smoothed, with a more constant increase from 2010 to 2020. The F trajectories of the CMSY model are in line with the official assessment, below the reference point in both years. Nevertheless, in both cases, a reduction in fishing mortality from 2019 to 2020 is estimated, with a marked drop in the official assessment. Comparing the stock assessment results of demersal species to the fishing effort dynamics of bottom trawlers, it is possible to recognize a slightly different stock status between the main target species of OTB and TBB, with the target species of the second gear (common sole, spottail mantis shrimp) experiencing high benefit from the extra fishing activity reduction imposed by the pandemic restrictions. For the main target of the OTB fleet (hake, deepwater shrimp), just a minor decrease in fishing pressure was discerned. As regards hake, the official stock assessments over recent years were describing an increasing biomass trend from 2017, when the Pomo pit FRA was established. The biomass increase slightly improved in 2020, suggesting that the effect of the COVID pandemic on hake stock was negligible when compared to the effectiveness of the FRA (Chiarini et al., 2022). Red mullet was an exception; it is a target of OTB, and a large fishing mortality decrease was observed. Indeed, fishing mortality for red mullet has been decreasing almost steadily during the period comprised between 2010 and 2020, probably due to a positive effect of the spatial management measures in place. In fact, in the Adriatic Sea coastal bottom trawl (within 6 nautical miles) is banned for a few weeks after the summer fishing ban, protecting red mullet recruits starting their seasonal offshore migration. However, red mullet results have to be interpreted with caution because of the important flaws in the input data used both in the official assessment and in the present paper. As was already noted in STECF (2021b) and as it was explored in depth during the tentative benchmark assessment carried out by GFCM in 2022 (FAO, 2022c), issues were detected in the discard data and the fishery-independent data. Discarded data suffered from a reporting incoherence, while fishery-independent biomass is estimated from a survey plagued by important violations of the protocol, which influenced the detection of the recruitment. Therefore, caution is required when interpreting the red mullet results. Common cuttlefish is a separate case, since it is targeted by a mix of gears (TBB, as well as passive gears and OTB). This stock shows a countertrend compared to the other species analysed and lies alone in the red quadrant of the Kobe plot. The decreasing biomass trend was not curbed, and the fishing pressure was even increased in 2020, despite official statistics depicting a significant fishing effort reduction for passive gears and TBB. Nevertheless, the alarming status of cuttlefish had already been noted well before the pandemic (FAO-GFCM, 2019a), and the most recent stock assessment states that the biomass is below 0.5 MSY—a threshold that indicates possible recruitment impairment (Froese et al., 2017).

Small pelagic species, anchovy and sardine, proved to be under overexploitation and overexploited for both the 2019 and 2020 stock assessments. However, the most recent assessment shows an important increase in biomass and a decrease in fishing mortality for the anchovy stock. The critical situation of these two stocks is also confirmed by the official stock assessment in which $F_{current}$ overpass F_{MSY} and $B_{current}$ are well below the respective reference points, B_{lim} and B_{pa}, with a more critical situation for sardines (FAO, 2021c; FAO, 2022b). When considering the biomass estimated by the MEDIAS acoustic survey, the COVID pandemic does not seem to have any direct effect on these stocks. However, the CMSY model depicts a more marked increase in anchovy biomass. Since anchovies are mainly targeted by Italian PTM (STECF, 2020a), the biomass increase can be partially explained by the fishing effort reduction. In the case of sardines, the results of the CMSY models depict a minor change from 2019 to 2020. Considering the negligible fishing effort reduction attributed to PS, the fleet mainly targeting this resource, there is no evidence that COVID-19 had a positive effect on sardine stock in the Adriatic Sea.

Conclusions

The COVID-19 impact on fishery resources was unexpected and therefore difficult to study. The pandemic can be considered a sort of benchmark helping us to better understand how the effort management alone can have limited success in rebuilding the stocks in the short term by simply limiting the fishing days.

Accounting for the fishing effort reduction already foreseen in the management plan, the COVID imposed extra-activity reduction not balanced over the studied *metièrs*. On a 1-year basis, only a few fleets were affected while for others no effective activity reduction was observed. Moreover, the comparison between fishing effort metrics indicates that fishing vessels may have balanced the reduced number of fishing days by remaining more time at sea, thus potentially limiting the effects of the observed fishing pressure reduction. The case of TBB was unique, indicating a pandemic-related reduction in effort evenly allocated over 2020, which was confirmed by all the fishing effort metrics. On the contrary, the decrease of around 12% in fishing days observed for OTB (in line with the management plan objectives) was translated into a very limited reduction in terms of fishing hours and an increase in hours at sea.

The trend in catches was generally on a downward trend from 2019 to 2020. In some cases, the catch reduction was due to diminished fishing activity, while in other cases catch reduction was linked to diminished stock productivity. Based on the CMSY model results, some examples could be identified. The main target stock of TBB, common sole, as well as spottail mantis shrimp, increased in terms of biomass and showed fishing mortality at the MSY level after many years of overfishing. That said, a recovering trend status for these stocks had already been documented in assessment reports (FAO-GFCM, 2019b; FAO, 2021b), probably due to the effective management actions underway in the area, such as the coastal trawling ban (up to 4 nm) for 8 weeks from 2006 and the temporary extension of this spatial restriction up to 6 nm for 10 weeks since 2012 (EC, 2006; Armelloni et al., 2021). Conversely, the slight reduction in fishing pressure seems to have had a limited effect on those stocks in poor biomass status. As an example, the catch trend for common cuttlefish has been steadily declining over the last 6 years. The common cuttlefish biomass trend has been well below half of the B_{MSY} reference point from 2010, and it did not show any response to fishing effort reductions already noticed in the 2010–2019 period. Catch drop for this species may therefore be likely explained by low stock productivity instead of a decreased fishing pressure.

Therefore, the COVID-19 effect can be considered a positive accelerator of a recovery process already underway only when the fishing activity was effectively reduced. When the stock was not increasing its biomass, a sporadic fishing effort reduction might have had a negligible effect. The case of cuttlefish falls within this category and may suggest that stock rebuilding needs *ad-hoc* actions (i.e., more attention on restoring alive at sea the egg masses left on fishing devices or actions aimed at increasing spawning stock substrates; Grati et al., 2018).

In conclusion, similarly to other areas (Coll et al., 2021; Pita et al., 2021), our study shows that the COVID-19 restrictions that occurred in 2020 resulted in a low recovery effect on the status of target stocks. The severe COVID-19 effects on effort and catches were limited to a short period (March-May 2020), and the main impacts were on the markets and the supply chain, affected by price instability for a longer period (Pititto et al., 2021). Nevertheless, the study outputs might help us understand some strengths and caveats of a management system based on effort control. In particular, it emerged that limiting the fishing days was a measure capable of being circumvented by increasing the duration of fishing trips and/or by increasing fishing efficiency (Palomares and Pauly, 2019), especially if the foreseen reduction is moderate. There is no drive to encourage more severe limitations to effort, which is likely to create conflicts between the fishery sector and the management system, but we stress the importance of evaluating alternative management measures. Echoing a recent work focusing on the revision of management measures (Fiorentino and Vitale, 2021), and considering also the conclusion from Cardinale et al. (2017) evidencing the ineffectiveness of the putative effort reductions to control fishing mortalities, we support the need to integrate input controls with stock- and fleet-specific measures, which are going to decrease fishing mortality toward MSY levels.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://github.com/CNRFisheries/COVID-19-effects-on-target-stocks-in-the-Adriatic-Sea.

Author contributions

GS conceived the original idea, collated data, and implemented the stock assessment models. SA provided information on official stock assessment. EA validated the data and provided information on official stock assessment. IC, AD, and IL provided information on the MEDIAS survey. FM and MS provided information on official stock assessment. SG performed the statistical analysis. GC provided information on the environmental parameters and supervised the experiment. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.920974/full#supplementary-material

References

Althouse, B. M., Wallace, B., Case, B., Scarpino, S. V., Berdhal, A., White, E. R., et al. (2020)The unintended consequences of inconsistent pandemic control policies. In: *medRxiv : the preprint server for health sciences* (Cold Spring Harbor Laboratory Press). (Accessed 11 April 2022).

Amoroso, R. O., Pitcher, C. R., Rijnsdorp, A. D., McConnaughey, R. A., Parma, A. M., Suuronen, P., et al. (2018). Bottom trawl fishing footprints on the world's continental shelves. *Proc. Natl. Acad. Sci.* 115, E10275–E10282. doi: 10.1073/pnas.1802379115

Anonymous (2017). *MEDITS-handbook* (MEDITS Working Group), 106. Available at: http://www.sibm.it/MEDITS 2011/principaledownload.htm.

Armelloni, E. N., Scanu, M., Masnadi, F., Coro, G., Angelini, S., and Scarcella, G. (2021). Data poor approach for the assessment of the main target species of rapido trawl fishery in Adriatic Sea. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.552076

Bennett, N. J., Finkbeiner, E. M., Ban, N. C., Belhabib, D., Jupiter, S. D., Kittinger, J. N., et al. (2020). The COVID-19 pandemic, small-scale fisheries and coastal fishing communities. *Coast. Manage.* 48, 336–347. doi: 10.1080/08920753.2020.1766937

Ben Rais Lasram, F., Guilhaumon, F., Albouy, C., Somot, S., Thuiller, W., and Mouillot, D. (2010). The Mediterranean Sea as a 'cul-de-sac' for endemic fishes facing climate change. *Global Change Biol.* 16, 3233–3245. doi: 10.1111/j.1365-2486.2010.02224.x

Bouch, P., Minto, C., and Reid, D. G. (2020). Comparative performance of data-poor CMSY and data-moderate SPiCT stock assessment methods when applied to data-rich, real-world stocks. *ICES J. Mar. Sci.* 78.1:264–276. doi: 10.1093/icesjms/fsaa220/6032767

Campanelli, A., Grilli, F., Paschini, E., and Marini, M. (2011). The influence of an exceptional po river flood on the physical and chemical oceanographic properties of the Adriatic Sea. *Dynamics Atmospheres Oceans* 52, 284–297. doi: 10.1016/j.dynatmoce.2011.05.004

Cardinale, M., Osio, G. C., and Scarcella, G. (2017). Mediterranean Sea: A failure of the European fisheries management system. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00072/full

Chiarini, M., Guicciardi, S., Zacchetti, L., Domenichetti, F., Canduci, G., Angelini, S., et al. (2022). Looking for a simple assessment tool for a complex task: Short-term evaluation of changes in fisheries management measures in the Pomo/Jabuka pits area (Central Adriatic Sea). *Sustainability* 14, 7742. doi: 10.3390/su14137742

Colloca, F., Scarcella, G., and Libralato, S. (2017). Recent trends and impacts of fisheries exploitation on Mediterranean stocks and ecosystems. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00244

Coll, M., Ortega-Cerdà, M., and Mascarell-Rocher, Y. (2021). Ecological and economic effects of COVID-19 in marine fisheries from the northwestern Mediterranean Sea. *Biol. Conserv.* 255, 108997. doi: 10.1016/j.biocon.2021.108997

Coll, M., Santojanni, A., Palomera, I., and Arneri, E. (2009). Food-web changes in the Adriatic Sea over the last three decades. *Mar. Ecol. Prog. Ser.* 381, 17–37. doi: 10.3354/meps07944

Coro, G., Bove, P., Armelloni, E. N., Masnadi, F., Scanu, M., and Scarcella, G. (2022a). Filling gaps in trawl surveys at Sea through spatiotemporal and environmental modelling. *Front. Mar. Sci.* 1106. doi: 10.3389/fmars.2022.919339/abstract

Coro, G., Bove, P., and Ellenbroek, A. (2022b). Habitat distribution change of commercial species in the Adriatic Sea during the COVID-19 pandemic. *Ecol. Inf.* 69, 101675. doi: 10.1016/j.ecoinf.2022.101675

Coro, G., Tassetti, A. N., Armelloni, E. N., Pulcinella, J., Ferrà, C., Sprovieri, M., et al. (2022c). COVID-19 lockdowns reveal the resilience of Adriatic Sea fisheries to forced fishing effort reduction. *Sci. Rep.* 12, 1052. doi: 10.1038/s41598-022-05142-w

EC (2006). *Council regulation (EC) no 1967/2006 of 21 December 2006 concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea, amending regulation (EEC) no 2847/93 and repealing regulation (EC) no 1626/94.*

Efron, B., and Hastie, T. (2016) *Computer age statistical inference: Algorithms, evidence, and data science*, 1–475.

Efron, B., and Tibshirani, R. (1993) *A n introduction to the practice. cindy.informatik.uni-bremen.de*. Available at: http://cindy.informatik.uni-bremen.de/cosy/teaching/CM_2011/Eval3/pe_efron_93.pdf (Accessed 6 April 2022).

Eigaard, O. R., Bastardie, F., Hintzen, N. T., Buhl-Mortensen, L., Buhl-Mortensen, P., Catarino, R., et al. (2017). The footprint of bottom trawling in European waters: Distribution, intensity, and seabed integrity. *ICES J. Mar. Sci.* 74, 847–865. doi: 10.1093/icesjms/fsw194

EU (2020) *European Union fleet register*. Available at: https://webgate.ec.europa.eu/fleet-europa/search_en (Accessed 1 June 2020).

FAO (1999). *Report of the first session of the scientific advisory committee* (Rome: Rome, Italy), 52. 23-26 March 1999. FAO Fisheries Report No. 601.

FAO (2020a) *How is COVID-19 affecting the fisheries and aquaculture food systems* (Rome). Available at: https://www.fao.org/policy-support/tools-and-publications/resources-details/fr/c/1271431/ (Accessed 14 April 2022).

FAO (2020b). *The state of Mediterranean and black Sea fisheries 2020*. 172.

FAO (2021a) *Scientific advisory committee on fisheries (SAC) working group on stock assessment of demersal species (WGSAD), online, 18–23 January 2021 (western Mediterranean) online, 25–30 January 2021 (central and eastern Mediterranean and Adriatic Sea)*. Available at: https://www.fao.org/gfcm/technical-meetings/detail/ru/c/1412431/.

FAO (2021b). *Scientific advisory committee on fisheries (SAC) working group on stock assessment of demersal species (WGSAD) - benchmark session for the assessment of common sole in GSA 17 , online, 12-16 April 2021*. 70.

FAO (2021c) *Working group on stock assessment of small pelagic species (WGSASP)*. Available at: https://www.fao.org/gfcm/technical-meetings/detail/ru/c/1412431/.

FAO (2021d) *Scientific advisory committee on fisheries (SAC) fifth meeting of the subregional committee for the Adriatic Sea (SRC-AS) online, 20–23 April 2021*. Available at: https://www.fao.org/gfcm/technical-meetings/detail/en/c/1410712/.

FAO (2022a) *Scientific advisory committee on fisheries (SAC) working group on stock assessment of demersal species (WGSAD) (western Mediterranean) (central and eastern Mediterranean and Adriatic Sea), 2022*. Available at: https://www.fao.org/gfcm/technical-meetings/detail/en/c/1506058/.

FAO (2022b). *Scientific advisory committee on fisheries (SAC) working group on stock assessment of small pelagic species (WGSASP)* Vol. 11 (Session on the assessment of European anchovy and sardine in the Adriatic Sea Online.), 67. Available at: https://www.fao.org/gfcm/technical-meetings/detail/en/c/1542569/.

FAO (2022c) *Working group on stock assessment of demersal species (WGSAD) benchmark session for the assessment of red mullet in GSAs*. Available at: https://www.fao.org/gfcm/technical-meetings/detail/en/c/1507459/.

FAO-GFCM (2019a). *Scientific advisory committee on fisheries (SAC) working group on stock assessment of demersal species (WGSAD)*. 1–68.

FAO-GFCM (2019b). *Working group on stock assessment of demersal species (WGSAD) FAO headquarters, Rome, Italy, 19–24 November 2018 FINAL REPORT*. 1–68.

Fiorentino, F., and Vitale, S. (2021). How can we reduce the overexploitation of the Mediterranean resources? *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.674633

Fortibuoni, T., Aldighieri, F., Giovanardi, O., Pranovi, F., and Zucchetta, M. (2015). *Climate impact on Italian fisheries (Mediterranean sea). regional environmental change* Vol. 15 (Springer Verlag), 931–937.

Fortibuoni, T., Giovanardi, O., Pranovi, F., Raicevich, S., Solidoro, C., and Libralato, S. (2017). Analysis of long-term changes in a Mediterranean marine ecosystem based on fishery landings. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00033

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., and Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish Fisheries* 18, 506–526. doi: 10.1111/faf.12190

Froese, R., and Pauly, D. (2019). *Fishbase* (World Wide Web electronic publication).

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A. C., Dimarchopoulou, D., et al. (2018). Status and rebuilding of European fisheries. *Mar. Policy* 93, 159–170. doi: 10.1016/j.marpol.2018.04.018

Galdelli, A., Armelloni, E. N., Ferrà, C., Pulcinella, J., Scarcella, G., and Tassetti, A. N. (2021). *R4AIS: An r workflow to process AIS data for fishery* (Zenodo). doi: 10.5281/zenodo.4761890

Grati, F., Fabi, G., Scarcella, G., Guicciardi, S., Penna, P., Scanu, M., et al. (2018). Artificial spawning substrates and participatory research to foster cuttlefish stock recovery: A pilot study in the Adriatic Sea. *PloS One* 13, e0205877. doi: 10.1371/journal.pone.0205877

Grati, F., Scarcella, G., Polidori, P., Domenichetti, F., Bolognini, L., Gramolini, R., et al. (2013). Multi-annual investigation of the spatial distributions of juvenile and adult sole (Solea solea l.) in the Adriatic Sea (northern Mediterranean). *J. Sea Res.* 84, 122–132. doi: 10.1016/j.seares.2013.05.001

Hale, T., Angrist, N., Goldszmidt, R., Kira, B., Petherick, A., Phillips, T., et al. (2021). A global panel database of pandemic policies (Oxford COVID-19 government response tracker). *Nat. Hum. Behav.* 5, 529–538. doi: 10.1038/s41562-021-01079-8

Hall-Spencer, J., Froglia, C., Atkinson, R. J. A., and Moore, P. G. (1999). The impact of rapido trawling for scallops,Pecten jacobaeus(L.), on the benthos of the gulf of Venice. *ICES J. Mar. Sci.* 56, 111–124. doi: 10.1006/jmsc.1998.0424

Jardim, E., Millar, C. P., Mosqueira, I., Scott, F., Osio, G. C., Ferretti, M., et al. (2014). What if stock assessment is as simple as a linear model? the a4a initiative. *ICES J. Mar. Sci.* 72, 232–236. doi: 10.1093/icesjms/fsu050

Leonori, I., Tičina, V., Giannoulaki, M., Hattab, T., Iglesias, M., Bonanno, A., et al. (2021). History of hydroacoustic surveys of small pelagic fish species in the European Mediterranean Sea. *Mediterr. Mar. Sci.* 22, 751–768. doi: 10.12681/mms.26001

Love, D. C., Allison, E. H., Asche, F., Belton, B., Cottrell, R. S., Froehlich, H. E., et al. (2021). Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. *Global Food Secur.* 28, 100494. doi: 10.1016/j.gfs.2021.100494

Marini, M., Bombace, G., and Iacobone, G. (2017). *Il mare adriatico e le sue risorse*. Carlo Saladino Editore (Palermo, Italy), 267.

Methot, R. D., and Wetzel, C. R. (2013). Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Res.* 142, 86–99. doi: 10.1016/j.fishres.2012.10.012

Palomares, M. L. D., Froese, R., Derrick, B., Meeuwig, J. J., Nöel, S. L., Tsui, G., et al. (2020). Fishery biomass trends of exploited fish populations in marine ecoregions, climatic zones and ocean basins. *Estuarine Coast. Shelf Sci.* 243, 106896. doi: 10.1016/j.ecss.2020.106896

Palomares, M., and Pauly, D. (2018). *SeaLifeBase. version (02/2018).*

Palomares, M. L. D., and Pauly, D. (2019) *On the creeping increase of vessels' fishing power. ecology and society*. Available at: https://www.jstor.org/stable/26796991?casa_token=2VHjx1yYs9gAAAAA:I4CSmzHEIhCa1yRL_5cO71994yZ34Xao7e_KBkq5KJxo9Z98ehGh-latk2K-bUSSjeIzgOTO5oiT7U3ARkIvav8VHDm3GMEr8tXBxbIXquB2lbXq9SkZg (Accessed 4 May 2020).

Payne, M. R., and Hintzen, N. T. (2013). *FLSAM: FLSAM, an implementation of the state-space assessment model for FLR.*

Pedersen, M. W., and Berg, C. W. (2017). A stochastic surplus production model in continuous time. *Fish Fisheries* 18, 226–243. doi: 10.1111/faf.12174

Pita, P., Ainsworth, G. B., Alba, B., Anderson, A. B., Antelo, M., Alós, J., et al. (2021). First assessment of the impacts of the COVID-19 pandemic on global marine recreational fisheries. *Front. Mar. Sci.* 8, 735741. doi: 10.3389/fmars.2021.735741

Pititto, A., Rainone, D., Sannino, V., Chever, T., Herry, L., Parant, S., et al. (2021) *Research for PECH committee – impacts of the COVID-19 pandemic on EU fisheries and aquaculture, epartment for structural and cohesion policies, Brussels.* Available at: https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2021)690880.

R Core Team (2022). *R: A language and environment for statistical computing* (Vienna, Austria: Version 4.1.3. R Foundation for Statistical Computing).

Russo, E., Anelli Monti, M., Toninato, G., Silvestri, C., Raffaetà, A., and Pranovi, F. (2021). Lockdown: How the COVID-19 pandemic affected the fishing activities in the Adriatic Sea (Central Mediterranean Sea). *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.685808

Russo, T., Catucci, E., Franceschini, S., Labanchi, L., Libralato, S., Sabatella, E. C., et al. (2022). Defend as you can, react quickly: The effects of the COVID-19 shock on a Large fishery of the Mediterranean Sea. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.824857

Scarcella, G., Grati, F., Raicevich, S., Russo, T., Gramolini, R., Scott, R. D., et al. (2014). Common sole in the northern and central Adriatic Sea: Spatial management scenarios to rebuild the stock. *J. Sea Res.* 89, 12–22. doi: 10.1016/j.seares.2014.02.002

Spedicato, M. T., Massutí, E., Mérigot, B., Tserpes, G., Jadaud, A., and Relini, G. (2019). The medits trawl survey specifications in an ecosystem approach to fishery management. *Scientia Marina* 83, 9–20. doi: 10.3989/scimar.04915.11X

STECF (2020a). *Scientific, technical and economic committee for fisheries (STECF) - the 2020 annual economic report on the EU fishing fleet (STECF 20-06)* (Luxembourg: Publications Office of the European Union), 302p. Available at: http://stecf.jrc.ec.europa.eu/documents/43805/581354/2013-09_STECF+13-15+-+AER+EU+Fleet+2013_JRC84745.pdf.

STECF (2020b). *Scientific, technical and economic committee for fisheries (STECF)- stock assessments: demersal stocks in the western Mediterranean Sea (STECF-20-09)* (Luxembourg: EUR 28359 EN, Publications Office of the European Union). Available at: https://stecf.jrc.ec.europa.eu/documents/43805/1446742/STECF+16-14+-+Methods+for+MED+stock+assessments_JRC102680.pdf.

STECF (2020c). *Scientific, technical and economic committee for fisheries (STECF) stock assessments in the Mediterranean Sea – Adriatic, Ionian and Aegean seas (STECF-20-15)* (Luxembourg: Publications Office of the European Union). Available at: https://stecf.jrc.ec.europa.eu/documents/43805/1446742/STECF+16-14+-+Methods+for+MED+stock+assessments_JRC102680.pdf.

STECF (2021a). *Scientific, technical and economic commi ttee for Fi sheries (STECF) – fisheries dependent -information – FDI (STECF-21-12)* (Luxembourg,2021: Publications Office of the European Union).

STECF (2021b). *Scientific, technical and economic committee for fisheries (STECF) – stock assessments in the Mediterranean Sea 2021 – (Adriatic and Ionian seas) (STECF-21-15)* (Luxembourg,2021: Publications Office of the European Union).

White, E. R., and Hébert-Dufresne, L. (2020). State-level variation of initial COVID-19 dynamics in the united states. *PloS One* 15, e0240648. doi: 10.1371/journal.pone.0240648