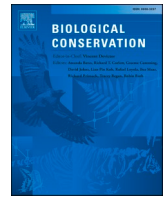




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Ecological and economic effects of COVID-19 in marine fisheries from the Northwestern Mediterranean Sea

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ABSTRACT

The SARS-CoV-2 coronavirus pandemic starting at the end of 2019 impacted many human activities. We analysed the abrupt reduction in fishing pressure of the mixed small-scale and industrial fisheries in the Catalan Sea, Spanish Mediterranean, and resulting ecological and economic impacts during the first half of 2020. We used detailed fisheries data on fishing effort, landings, revenues, landings per unit of effort (LPUE) and revenues per unit of effort from January to June 2020, and complemented it with the outcomes of a marine ecosystem model. We analysed data from 2017 to 2019 and compared these to 2020 to characterise changes in the fishing activity from before (January–February) to during (March–May) the lockdown. Fishing effort during the lockdown dropped by 34%, landings were down by 49% and revenues declined by 39% in comparison with the same period in 2017–2019. LPUEs did not show significant changes during the lockdown, with the exception of shrimp species, especially the deep-water rose shrimp, which significantly increased in LPUE during March–May. These increases may reflect positive effects of reduced fishing on fast-growing species. Positive effects mostly disappeared in June 2020 with the relaxation of the lockdown. In agreement, the ecological simulations projected slight short-term increases of biomass for fast-growing, small-sized organisms during 2020, which quickly vanished when fishing resumed, and which had no detectable ecosystem effects. Three additional alternative ecological simulations illustrated that to substantially recover commercial species and ensure ecosystem sustainability in the study area, a sustained and notable reduction of fishing activity would be needed.

1. Introduction

During the last days of 2019 and up to the day of writing, humanity has been immersed in an unprecedented situation due to the eruption of the SARS-CoV-2 coronavirus pandemic. This pandemic, referred to as the COVID-19 pandemic after the disease caused by the virus, has caused a global acute human health crisis with tragic consequences.

In response, governments have implemented drastic policies to prevent infections or ‘flatten the curve’ of outbreaks (Diffenbaugh et al., 2020; Le Quére et al., 2020). As a result, human activities have been considerably reduced in many regions of the world for weeks to months on end. These human confinements may be one of the largest “experiment” of abrupt and intense cessations of anthropogenic activities to date, providing a historic snapshot of the effects on human wellbeing, the environment and wildlife, including the oceans (Bates et al., 2020;

Coll, 2020; Corlett et al., 2020; Manenti et al., 2020).

The principal aim of this article is to analyse in detail the ecological and economic effects of the COVID-19 during the core period of the crisis on the Catalan Sea mixed small-scale and semi-industrial fisheries in the Balearic Sea, Mediterranean (Spain). Mediterranean fisheries target a large variety of fish and invertebrates species and use a large number of landing sites (Bas, 2002; Coll et al., 2014b; Leonart and Maynou, 2003; Papaconstantinou and Farrugio, 2000). The Catalan Sea fisheries operate in the Balearic Sea, mostly between the Ebro River and the Spanish French border, and within the FAO subarea GSA06. Catches from predominantly the continental shelf and mid-continental slope are typically landed daily. Artisanal, and small-scale and semi-industrial fleets are present, but most important fleets in terms of landings are semi-industrial, composed of bottom trawlers, purse seiners and longliners, including the tuna fleets.

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In 2020, the fishing fleet of the Catalan Sea consisted of 724 vessels (Table 1, Supplementary Material). While more than 260 different fished species have been recorded in the last ten years, 15 species represented 74% of landings and 68% of revenues in 2019 (Table 2, Supplementary Material). These fisheries mainly sell to local and regional fresh fish markets (ICATMAR, 2020a). Except for the minoritarian tuna seine and surface longline fleet, all fleet segments in the study area return daily to port to sell most of their landings in fresh. Revenues are highly dependent on the HORECA (hotels, restaurants and catering) channel, where the best prices are achieved. In Spain, 29% of fresh fish consumption occurs out-of-home (EUMOFA, 2019). Nevertheless, the dependence on the HORECA varies per commercial species. Regional landings in the study area represent 22% of the total fresh fish consumed and 16% of the total fish consumption. Local fish markets are also very dependent on external factors and trade (Generalitat de Catalunya, 2020a).

In the last 10 years before the pandemic, the main fisheries in the area were in a delicate situation. A mixture of increasing costs and decreasing incomes (−27%, constant prices) associated with a decreasing volumes of landings (−19%) and the decrease in €/kg ratio (−10%, constant prices) led to a 30% reduction in fishing vessels (Generalitat de Catalunya, 2020b). Despite this decline, absolute fishing effort increased (Coll et al., 2014a; Gorelli et al., 2016; Sardà, 2017) with concerning impacts on key targeted stocks (Table 1) due to the low selectivity of nets, small captured sizes and low abundances at sea (Bas, 2009; ICATMAR, 2020a, 2020b; Sardà, 2017). This situation is likely representative of other areas in the Mediterranean and southern European Seas (Colloca et al., 2017; FAO, 2018, 2020b, 2020c; Fernandes et al., 2017).

Overall, marine fisheries changed dramatically during COVID-19 (FAO, 2020a). Global industrial fishing activity was reduced by 6.5% at the end of April 2020 compared to same period in 2019, or by 10% if calculated from the date the global pandemic was declared (Global Fishing Watch, 2020). Regionally, fishing activity reductions varied. As of early April 2020, cumulative fishing activity in China's EEZ was down by nearly 40% since the Chinese New Year, with approximately 1.2 million fewer fishing hours. Chinese fishing activity has since recovered (Global Fishing Watch, 2020). In Peru, having the world's largest commercial fishery, fishing activity dropped by 80% (Global Fishing Watch, 2020), while Indonesian shark trade reportedly declined by 70% (Mongabay, 2020). In European waters, many large fishing nations (e.g., Spain, Italy) saw their fishing substantially reduced during the lockdown, with reductions up to 50% or more until late May 2020 when compared to preceding years (Global Fishing Watch, 2020; Ortega and Mascarell, 2020).

During COVID-19 core months, local and global demand for seafood, the most traded food commodity in the world, was interrupted (Knight et al., 2020; Ortega and Mascarell, 2020; Stoll et al., 2020). Reduced demand lowered local prices due to HORECA channel and fresh markets closures, with a supply that in some cases surpassed demand (Ortega and

Table 1

STEFEC stock assessments relevant to Catalan fisheries. Source (STEFEC, 2019), European anchovy and sardine (STEFEC, 2020). Figures correspond to 2018, but European anchovy and sardine data is from 2016.

Specie	GSA Area	% change in fishing effort to achieve Fmsy	Biomass (status)
European hake	1,5,6,7	−63%	Low/stable
Red Mullet	6	−69%	Low/stable
Norway lobster	6	−71%	Low/stable
Blue and red shrimp	6,7	−65%	Fluctuating
Deep-water rose shrimp	1,5,6,7	−55%	Increasing
European anchovy	6	−16%	Fluctuating
European sardine	6	−61%	Low

Mascarell, 2020). COVID-19 especially impacted small-scale fishing activities (Knight et al., 2020; Ortega and Mascarell, 2020; WWF, 2020), which supply half of the demand for seafood and employ 90% of world's fishers (FAO, 2020c). Small-scale gear fisheries directly rely on local fresh markets and trade activities, which collapsed immediately when the COVID-19 pandemic emerged (FAO, 2020a). Despite noticeable increases in direct sales via the Internet, high uncertainties in the food supply and interruptions in traditional value chains meant that fisheries recoveries depended on the reopening of markets, restaurants, trade routes and other large-scale activities associated with the consumption of seafood, such as tourism (Ortega and Mascarell, 2020; Stoll et al., 2020; WWF, 2020).

Before the pandemic, global fisheries supplied society with ~96.4 million tons of fish, ~88% of which were used for direct consumption. With 38.89 million people engaged in the primary fisheries sector and ~4.56 million fishing vessels in operation, global fisheries industry exported annually USD 164.1 billion (FAO, 2020c). Despite some preliminary data (Ortega et al., 2020), the full consequences of the fisheries reduction during the lockdown are still to be quantified. Disrupted local and global value chains of seafood production provide a unique opportunity to understand fisheries functioning and their impacts on marine resources and ecosystems. This increased understanding can be used to promote market diversification alternatives as key insurance for future fisheries resilience and sustainability (Knight et al., 2020; Ortega and Mascarell, 2020). The study of the effects of the COVID-19 lockdown provides humanity with unique insights into the magnitude and direction of change that is needed to trigger sustained positive responses from marine resources and ecosystems, while minimizing the negative effects of the abrupt nature of the lockdowns.

2. Material and methods

2.1. Study area

Our study area is located within the Balearic Sea in the Northwestern Mediterranean (Fig. 1). The region is within the most productive area of the Mediterranean Sea (Bosc et al., 2004) due to upwelling influenced by wind, fresh water inputs from the Rhone and Ebro rivers, and a wide counter-clockwise current running along the continental slope (Agostini and Bakun, 2002; Salat, 1996). The area hosts essential fish habitats such as spawning and nursery areas for small pelagic and demersal fish (Giannoulaki et al., 2011; Tugores et al., 2019). The region is also relevant for seabirds colonies, marine mammals, marine turtles, and species at risk (Coll et al., 2015).

2.2. Economic analysis

Spain was in a state of alarm (i.e. state of emergency) from March 15th to June 21st 2020, during which citizen movement and economic measures were limited (Fig. 2). In this study we analysed the period from January 1st to the June 30th 2020, which covered the entire COVID-19 state of alarm and two and a half months prior, to consider pre-crisis data in our analysis (Fig. 2). The month of June 2020 was included as a reference where most of the fishing activity had recovered. We also used data from 2017 to 2019 for trend comparison with the COVID-19 year.

Available data regarding total landings (tons), total revenues from first sell points (€), fishing effort (n° vessels-day), landings productivity as Landings Per Unit of fishing Effort (LPUE, kg/n° vessel-day), and economic productivity as Euros Per Unit of fishing Effort (EPUE, €/n° vessel-day) were obtained from the Catalan Government official daily discharge through the Institute of Marine Science (ICM-CSIC), Barcelona, Spain. The original data was disaggregated by species, fishing boat and fleet, harbour, and day.

To analyse the impact of COVID-19, a monthly sum of key variables (landings, revenues, fishing effort, LPUE and EPUE) for the whole fleet

Table 2

Percentage (%) of change in fishing effort, landings, revenues, landings productivity and economic productivity of the total fishing sector and fishing sub-sectors between January–February and March–May 2017–2019 and 2020. The difference between the % of change between March–May and January–February represents the COVID-19 effect.

	% Effort (20/17-19)		% Landings (20/17-19)		% Revenue (20/17-19)		% LPUE (20/17-19)		% EPUE (20/17-19)	
	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY
Total	1%	-34%	-19%	-49%	-11%	-39%	-20%	-24%	-12%	-8%
Bottom trawling	-7%	-40%	-10%	-37%	-11%	-42%	-5%	5%	-5%	-2%
Purse seiners	-11%	-52%	-30%	-59%	-28%	-47%	-18%	-13%	-15%	16%
Small scale fisheries	19%	-19%	35%	4%	15%	-17%	14%	29%	-3%	0%
Bottom longliners	-22%	-39%	-31%	-42%	-30%	-47%	-7%	-8%	-7%	-18%

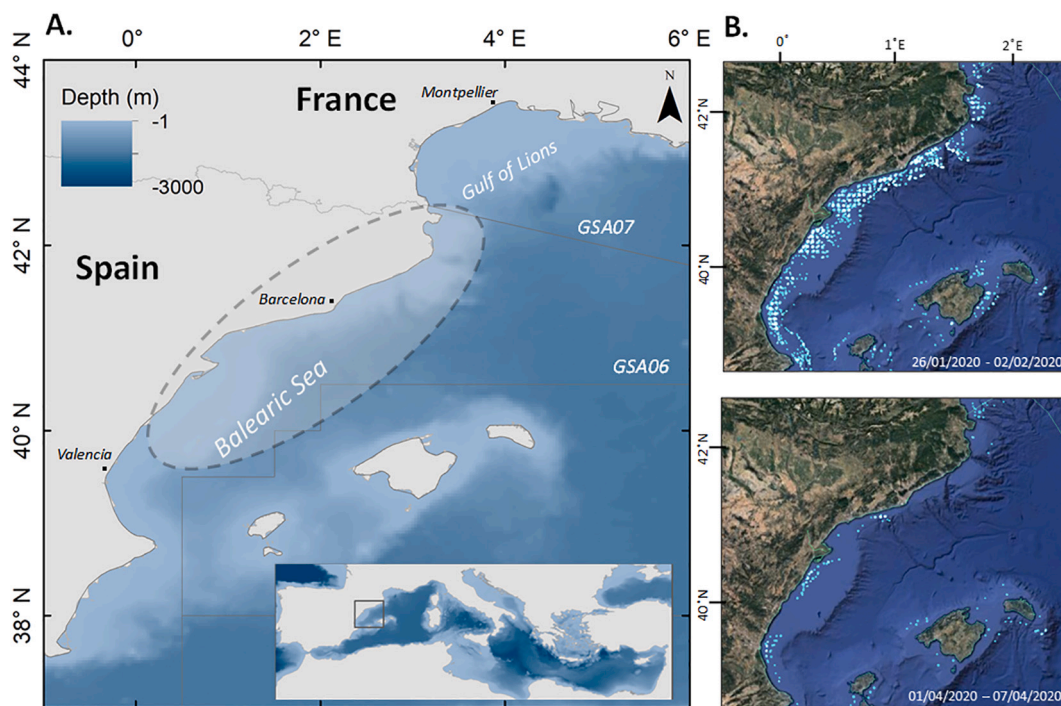


Fig. 1. A) Study area within the North-western Mediterranean Sea, and B) Comparison of fishing activity in the study area for two one-week periods: January 26 to February 2, 2020 (top panel) and April 1 to April 7, 2020 (Source: Global Fishing Watch, <https://globalfishingwatch.org>).

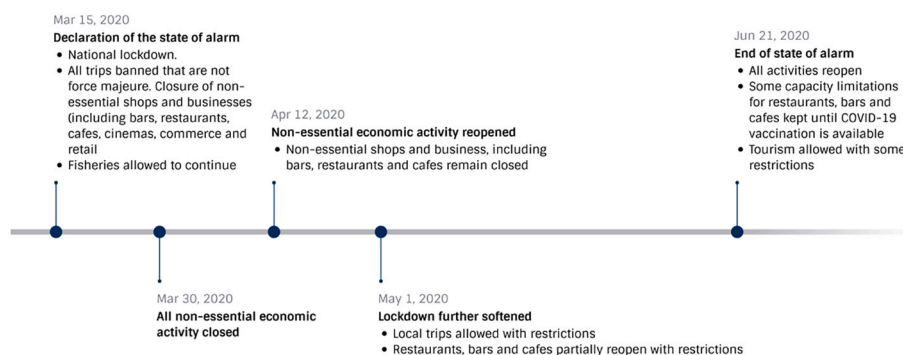


Fig. 2. Timetable lockdown measures to halt the spread of COVID-19 in Spain.

and for each main fleet segments (bottom trawling, purse seiners, bottom longliners and small-scale gear fisheries, Table 1 Supplementary Material), by several commercial species (Table 2 Supplementary Material) was compared with monthly values for the previous three years (2017–2019). A preliminary sensibility analysis was performed using

the previous five years (2015–2019) instead of three years, but as no major changes were obtained, results are not presented. Similarly, a weekly comparison analysis was discarded because data for ecological processes and economic impacts of the COVID-19 was not available at this frequency. In addition, tuna seiners and surface longliners fleet

segments were excluded because of their specific characteristics: very low number of vessels (4 and 12, respectively), very short periods of activity in the case of tune seine fleet, fishing trips lasting multiple days, and targeting only specific markets.

Landings and revenues changes were also affected long-term by sustained reduction in landings due to the poor state of the marine ecosystem (ICATMAR, 2020a). We therefore undertook a specific analysis to differentiate both elements. Long-term effects were isolated from the immediate effects of the lockdown using the difference between 2020 and 2017–2019 captures in January and February as reference values for pre-COVID-19 crisis and March to May for COVID-19 crisis period. The differences in this period previous the lockdown can be attributed to the long-term trend. Price comparisons for each period was performed using constant prices from the official Catalan Consumer Price Index (Generalitat de Catalunya, 2020a) thus correcting for inflation.

2.3. Ecological modelling analyses

The ecological analyses were performed using an available marine ecosystem model developed using Ecopath with Ecosim (EwE) approach (Christensen and Walters, 2004) that represents the southern area of the Catalan Sea (Coll et al., 2006). The model covers an area of 4500 km² of the continental shelf and upper slope associated with the Ebro River Delta, and incorporates main commercial fisheries. The model was fitted to data from 1978 to 2010 using time series of fishing effort to drive the model and relative catches and biomasses to compare projected to observed trends (Coll et al., 2013b; Coll et al., 2008). A spatial-temporal version of the model includes main environmental drivers of species distributions (Coll et al., 2019; Coll and Steenbeek, 2017; Coll et al., 2016b).

In this study, the time dynamic model was used with default parameterization (Coll et al., 2013b; Coll et al., 2008; Coll and Steenbeek, 2017; Coll et al., 2016b), where time series of fishing effort were updated to 2019. Afterwards, in 2020, values of fishing effort were modified according to the following five scenarios:

1. **S1-BAU**: business as usual, where fishing effort from 2019 was kept constant from 2020 to 2025, simulating no reduction of the fishing activity;
2. **S2-COVID19/3**: fishing effort for March to May 2020 was reduced to COVID-19 lockdown levels, based on the data analysis from our fisheries study. The effort observed in 2019 was used for June 2020 up to the end of 2025;
3. **S3-COVID19/12**: fishing effort in 2020 was reduced to reflect changes in fishing effort during the whole year, extending the reduction of fishing effort during March to May 2020 lockdown to December 2020. This scenario hypothesises a larger impact of COVID-19 in the fishing activity with a strong reduction of fishing effort during 2020. The effort observed in 2019 was used in 2021–2025 period;
4. **S4-COVID19/3Frw**: fishing effort in 2020 was reduced to reflect reductions in fishing effort during the months of the lockdown, and the reduction was extended until 2025, thus assuming a reduction per year from 2020 to 2025 equivalent to what was observed for real due to COVID-19 acute phase from March to May 2020.
5. **S5-COVID19/12Frw**: fishing effort in 2020 was reduced to reflect changes in fishing effort during to COVID-19 for the whole year, extending the reduction of fishing effort during the months of the lockdown to a full year, which continued forward for 5 years. This scenario illustrates a continued long term reduction of fishing effort during the whole 2020–2025 period in the same conditions as it was produced in the acute COVID-19 phase in March to May 2020.

Simulations run from 1978 to 2025, where fishing effort was modified in 2020 and onward according to the scenarios above. We analysed

model projections for biomass and landings of the principal commercial species (Table 2 Supplementary Material), in addition to ecological indicators that reflect the ecosystem impacts on fisheries, including biodiversity and conservation aspects. Selected indicators were: (1) biomass of fish (FishB) and (2) biomass of invertebrates (InvB), (3) the Kempton's Q diversity indicator (KQ), and (4) the Mean Trophic Level of the catch using trophic levels higher than 3.25 (MTI) (Ainsworth and Pitcher, 2006; Coll and Steenbeek, 2017; Pauly and Watson, 2005). These indicators were extracted using the ECOIND plug-in, which produces time series of indicators based on specific traits of modelled functional groups and the species within (Coll and Steenbeek, 2017). All ecosystem analysis were performed with EwE version 6.6.3.

2.4. Statistical analyses

General linear models (GLM) using the glm function of the R package "stats" with a Poisson or a quasi-Poisson family distribution (when the variance was larger than the mean) were used to test the effect of COVID-19 between 2017 and 2019 and 2020 on economic indicators of fishing (fishing effort, revenues, landings, LPUE and EPUE). The non-parametric Spearman rank correlation was used to test significant changes in the time series resulting from the ecological modelling projections (Spearman, 1904). All analyses and figures were done using R version 4.0.2.

3. Results

3.1. Economic activity by fishing fleet segment

The Spanish COVID-19 state of alarm reduced fishing activities in the study area from March 15th until June 2020 (Tables 2 and S3 Supplementary Material). Before COVID-19, fishing effort had increased by 1% in January–February 2020 in comparison with 2017–2019 with an uneven distribution: long liners, purse seiners and bottom trawlers showed a moderate decline in effort, while small-scale gear fisheries showed an increase of 19% (Table 2). Fishing effort significantly decreased by 34% during March–May 2020 (Fig. 3a, Tables 2 and S3 Supplementary Material, t-value = -2.5, p-value = 0.02) and was significantly higher for purse-seiners (52%) and bottom trawlers (40%) (Table 2, Fig. 3b, and Table S3 and Fig. S1 Supplementary Material). By June 2020, most fishing activities had recovered to an overall decline of 3% with respect to the 2017–2019 period.

Before COVID-19, landings already showed declines for purse seiners and bottom longliners, and an increase for small-scale gear fisheries of 35% (Table 2). This gap narrowed during the COVID-19 lockdown. Landings significantly decreased by 49% (Fig. 3b, Tables 2, S3 Supplementary Material, t-value = -2.72, p-value = 0.013) during March to May 2020, which corresponded to 15% of the annual average captures for 2017–2019. The reduction was larger and significant in purse seiners (59%) and bottom trawlers (37%) (Table 2, and Figs. S1 and S2 Supplementary Material). By June, landings had declined by 13% with respect to the 2017–2019 period (Fig. 3b).

Before COVID-19, all revenues were already in decline, with the exception of revenues from small-scale gear fisheries (Table 2). These declines increased during COVID-19. The COVID-19 lockdown led to a significant decrease in 39% in revenues (Fig. 3c, Tables 2 and S3 Supplementary Material, t-value = -2.19, p-value = 0.04), that corresponded to 12% of the annual mean revenue for 2017–2019. The analysis showed larger significant reductions for bottom longliners (47%) and trawlers (42%) (Table 2, and Figs. S1 and S3 Supplementary Material). By June, revenues had declined by 10% with respect to the 2017–2019 period (Fig. 3c).

Before COVID-19, landings per unit of fishing effort (LPUE) showed moderate declines, with the notable exception of small-scale gear fisheries (Table 2). Pre-crisis declines in LPUE for purse seiners were larger than during COVID-19. LPUE declined significantly by 24% with respect

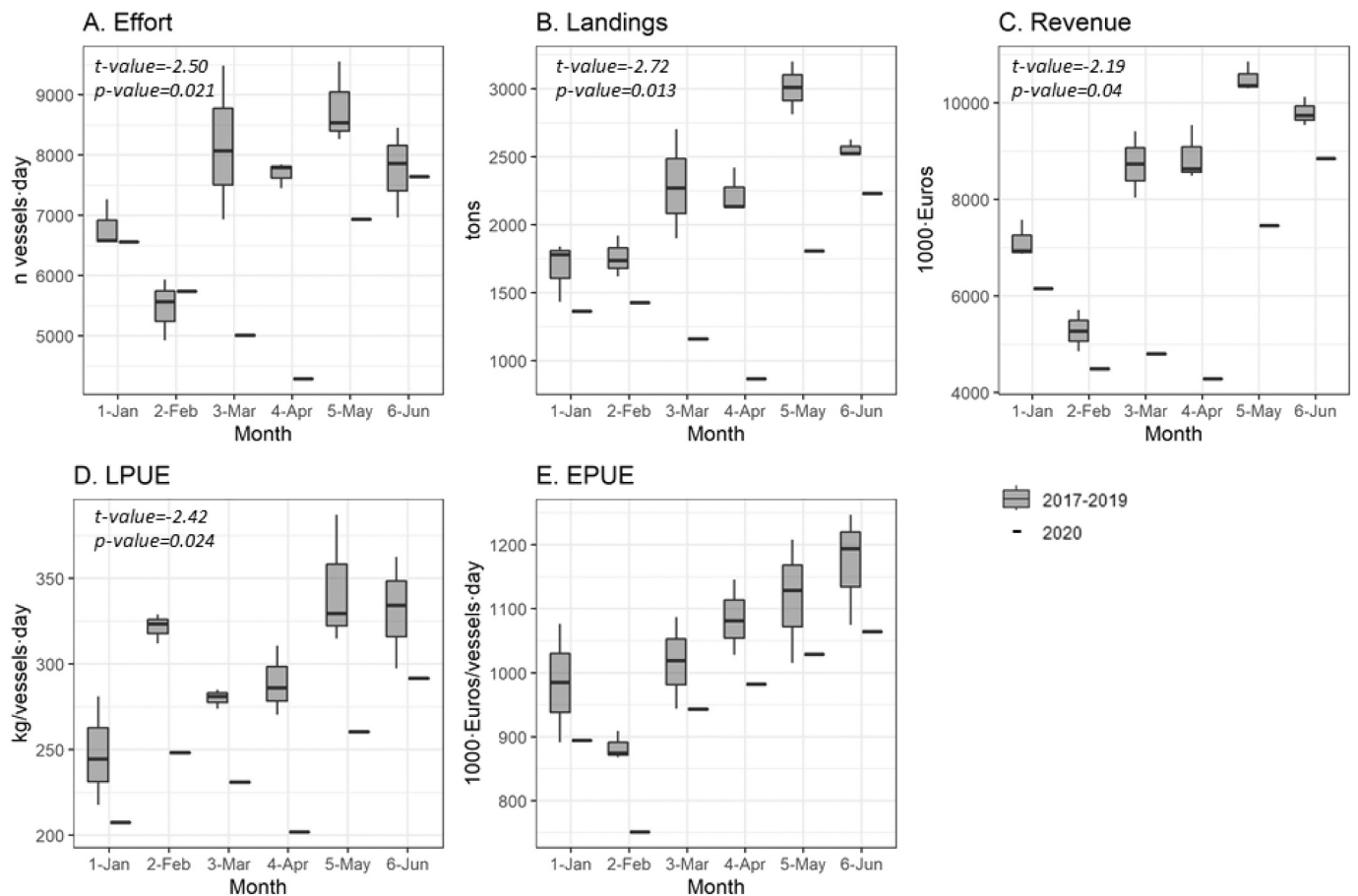


Fig. 3. Variation in 2020 total fishing activity in the study area, expressed in (a) landings (tonnes), (b) revenue (1000-€), (c) fishing effort (n° vessels/day), (d) landings per unit of fishing effort (LPUE, kg/n° vessel/day) and (e) euros per unit of fishing effort (EPUE, 1000-€/n° vessel/day) compared to 2017–2019.

to 2017–2019 in comparison to the 2020 lockdown (Fig. 3d, Tables 2 and S3 Supplementary Material, $t\text{-value} = -2.42$, $p\text{-value} = 0.02$). LPUE declines were larger and marginally significant for purse seiners (13%), while the LPUE of small-scale gear fisheries showed a significant increase of 29% (Table S3 Supplementary Material, $t\text{-value} = -1.9$, $p\text{-value} = 0.07$ and $t\text{-value} = 4.01$, $p\text{-value} < 0.001$, respectively) (Table 2,

and Figs. S2 and S4 Supplementary Material). By June, the LPUE had declined by 12% with respect to the 2017–2019 period (Fig. 3d).

Before COVID-19, revenue per unit of fishing effort (EPUE) showed declines for all fleet segments. EPUE showed a non-significant decline of 8% during the lockdown (Fig. 3e, Tables 2 and S3 Supplementary Material). By June, the EPUE had declined by 11% with respect to the

Table 3

Percentage (%) of change in landings, revenues, landings productivity and economic productivity of main commercial fish and invertebrate species between January–February and March–May 2017–2019 and 2020. The difference between the % of change between March–May and January–February represents the COVID-19 effect.

Commercial species	% Landings (20/17-19)		% Revenue (20/17-19)		%LPUE (20/17-19)		%EPUE (20/17-19)	
	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY	JAN-FEB	MAR-MAY
Commercial fish								
European hake (<i>Merluccius merluccius</i>)	-50%	-58%	-24%	-43%	-47%	-30%	-18%	-6%
Red mullet (<i>Mullus barbatus</i>)	-2%	-18%	-8%	-37%	3%	26%	-5%	-3%
European anchovy (<i>Engraulis encrasicolus</i>)	-45%	-61%	-32%	-52%	-26%	-23%	-2%	-1%
European sardine (<i>Sardina pilchardus</i>)	-20%	-57%	-23%	-36%	-23%	-16%	-28%	26%
Round sardinella (<i>Sardinella aurita</i>)	40%	-17%	88%	-5%	-3%	1%	34%	41%
Atlantic horse mackerel (<i>Trachurus trachurus</i>)	64%	2%	115%	24%	-19%	10%	8%	29%
Commercial invertebrates								
Blue and red shrimp (<i>Aristeus antennatus</i>)	1%	-22%	-4%	-39%	-15%	3%	-21%	-16%
Deep-water rose shrimp (<i>Parapenaeus longirostris</i>)	54%	-9%	1%	-51%	21%	37%	-21%	-27%
Norway lobster (<i>Nephrops norvegicus</i>)	69%	-36%	63%	-31%	62%	-7%	52%	5%
Spottail mantis shrimp (<i>Squilla mantis</i>)	4%	-26%	-2%	-32%	17%	27%	10%	15%
Blue crab (<i>Callinectes sapidus</i>)	184%	-1%	224%	-39%	96%	59%	88%	-15%
Common octopus (<i>Octopus vulgaris</i>)	-53%	-54%	-50%	-62%	-33%	-10%	-29%	-25%
Horned octopus (<i>Eledone cirrhosa</i>)	-1%	-63%	2%	-58%	-1%	-32%	-3%	-21%

2017–2019 period (Fig. 3e).

3.2. Landings, revenues and productivity of commercial fish and invertebrates

Landings of commercial fish species in 2020, prior to the lockdown, were already showing declines in comparison to 2017–2019 (Table 3). These declines were especially relevant for European hake (51%), European anchovy (48% decline) and European sardine (17% decline). Before COVID-19, landings increased for Atlantic horse mackerel (80%), round sardinella (45%) and red mullets (10%). Declines were stronger during the COVID-19 lockdown, or increases turned into declines. Revenues showed overall declines as well, with the exception of Atlantic horse mackerel. Revenues before COVID-19 showed smaller declines for hake, anchovy and sardine, and notable increases for round sardinella and horse mackerel in agreement with reported increases of catches.

Except for red mullets and Atlantic horse mackerel, the LPUE for the rest of analysed commercial fish species showed declines during COVID-19, which were marginally significant for hake and anchovy (Table 3 and Table S4 Supplementary Material, t -value = -1.9 , p -value = 0.07 and t -value = -1.96 , p -value = 0.06 , respectively). Before COVID-19 declines for hake and anchovy were higher and increases for Atlantic horse mackerel were lower, suggesting a positive impact on productivity during the lockdown, especially noticeable for Atlantic horse mackerel and red mullets (Fig. S5 Supplementary Material).

Before COVID-19, the EPUEs showed increases for round sardinella and Atlantic horse mackerel, but not for sardine, which showed declines in addition to hake, red mullets and anchovy (Figs. S5 and S6 Supplementary Material). During COVID-19, the EPUE did not show significant changes.

Contrary to fish species, landings of commercial invertebrates showed increases in 2020 in relation to 2017–2019 even before COVID-19, with the exception of common octopus that showed an intense decline of 50% (Table 3). These increases turned into moderate or large

declines for all the targeted species analysed during COVID-19. Revenues also declined during COVID-19 following catch patterns. Before COVID-19, revenues had shown extraordinary increases for blue crab, followed by Norway lobster and deep-water rose shrimp, while declines were already observed for common octopus.

During COVID-19, the LPUE of all crustaceans except benthic cephalopods increased (Fig. 4), with marginally significant increases for blue and red shrimp (Fig. 4a) and largely significant for the deep-water rose shrimp (Fig. 4b) (Tables 3 and S4 Supplementary Material, t -value = 1.97 , p -value = 0.06 and t -value = -3.58 , p -value = 0.002 , respectively). These increases were larger than the ones observed before COVID-19 for deep-water rose shrimp and mantis shrimp, suggesting that these fast-producing species benefitted from the temporary absence of fishing. Two species of invertebrates, Norway lobster and mantis shrimp showed non-significant increases of EPUE during COVID-19 in 2020 (Table 3 and Fig. 4). In contrast, the economic productivity of blue crab and Norway lobster declined in comparison with pre-crisis period (Table 3).

3.3. Ecological projections

Projections from the ecological model showed declines in biomass and catch for European hake and sardine under the “business as usual” (BAU) scenario when comparing 2020 to 2017–2019, matching observations of landings and LPUE (Table 3) during January–February 2020 (Tables S5 and S6 Supplementary Material). On the contrary, increases in biomasses and catches were projected for red mullets and Norway lobster, as observed in the fisheries data (Table 3). The functional groups representing “shrimps”, “crabs” and “cephalopods” showed an increase under the BAU scenario and mostly matched with observations for species falling in these categories, with the exception of cephalopods (Tables S5 and S6 Supplementary Material).

The COVID-19/3 simulation projected a decline of catches for all commercial species in 2020, while biomasses declined less than in BAU simulations for hake, anchovy, sardine, horse mackerel species, and

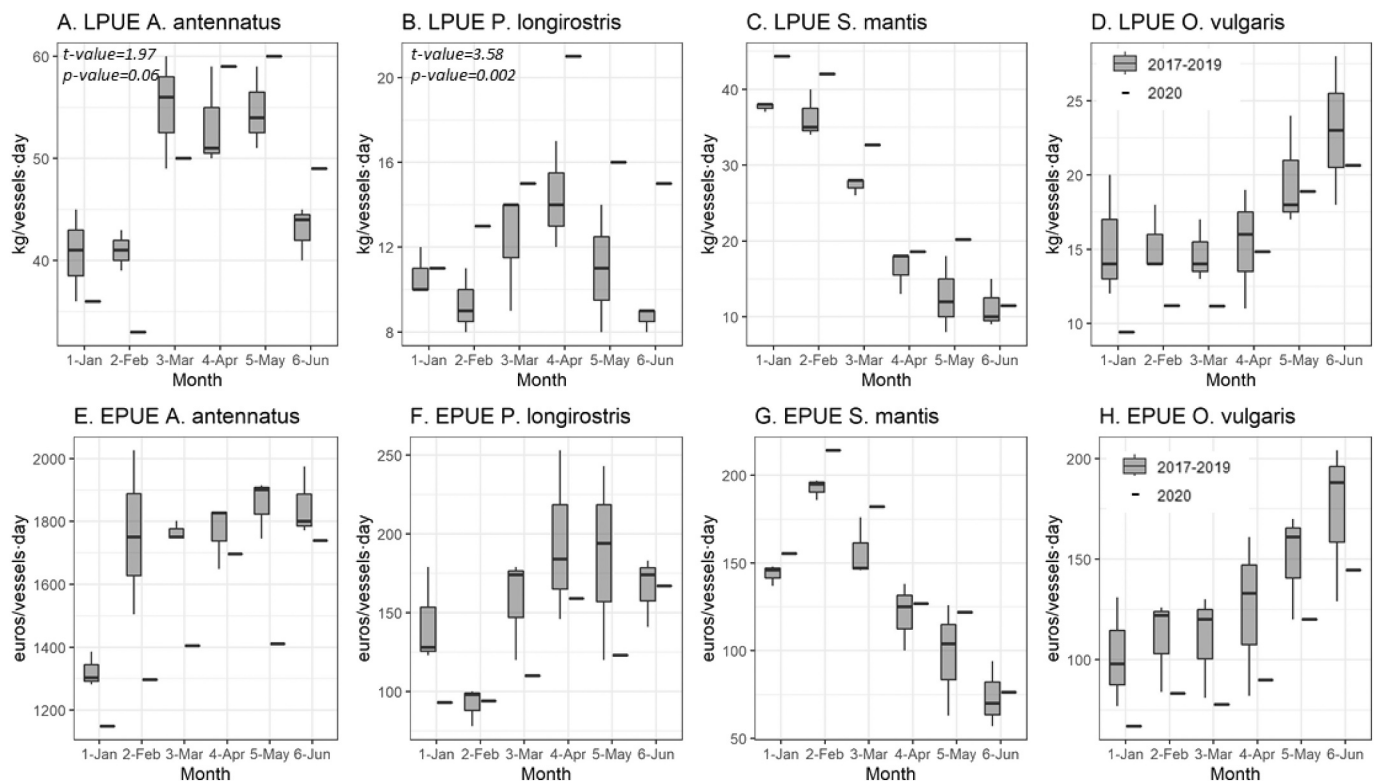


Fig. 4. Variation in 2020 landings per unit of fishing effort (LPUE, $\text{kg}/\text{n}^\circ \text{ vessel}/\text{day}$) and Euros per unit of fishing effort (EPUE, $1000\text{-}\text{€}/\text{n}^\circ \text{ vessel}/\text{day}$) compared to 2017–2019 for selected invertebrate species.

increased for red mullets, crabs, Norway lobster and cephalopods (Fig. 5, and Tables S5 and S6 Supplementary Material). These results showed similar directions of change as the observed data (Table 3). However, magnitudes of change substantially differed. Results projected in 2025 were very similar to those obtained under BAU. The COVID-19/12 simulation projected a lower reduction of biomasses respect to BAU (e.g. hake and sardine) and increases of biomass for other species (anchovy, shrimps, crabs, Norway lobster and cephalopods). On the contrary, catches were projected to decline substantially due to the reduced fishing activity by 42% for the remainder of 2020, but they had recovered by 2025 with an overall increase of 7% (Fig. 5, Tables S5 and S6 Supplementary Material).

The COVID-19/3Frw simulations, which used a decline in effort to the end of the simulation period, projected larger increases in 2025 biomasses for anchovy, crabs and cephalopods, with lower declines for hake (Fig. 5, and Tables S5 and S6 Supplementary Material). Finally, under COVID-19/12Frw simulations, that used a strong decline in

fisheries effort from 2020 to 2025 as if the lockdown in the first three months of 2020 would have lasted until the end of 2025, larger increases in biomasses in 2025 were observed for most targeted species and groups. Under this simulation and for the first time, a recovery for hake was achieved with a 6% increase in biomass with respect to 2017–2019. However, the generic group “shrimps” and “SPF” would still show declines. Sardine would not recover, although with less intense and non-significant declines than in any other simulation.

Results from ecological indicators reflected a degradation of the ecosystem with time under BAU, which was not substantially halted under the brief COVID-19 lockdown: they showed significant declines of FishB, and KQ and an increase in InvB during the BAU simulation, which did not substantially change under COVID-19/3 simulations (Fig. 6 and Table S7 Supplementary Material). Negative changes in FishB and KQ were projected to be slower under COVID-19/12, but at the end of 2025 indicators showed similar results as to BAU and COVID-19/3 simulations. Under COVID-19/3Frw simulation, a lower increase of InvB (with

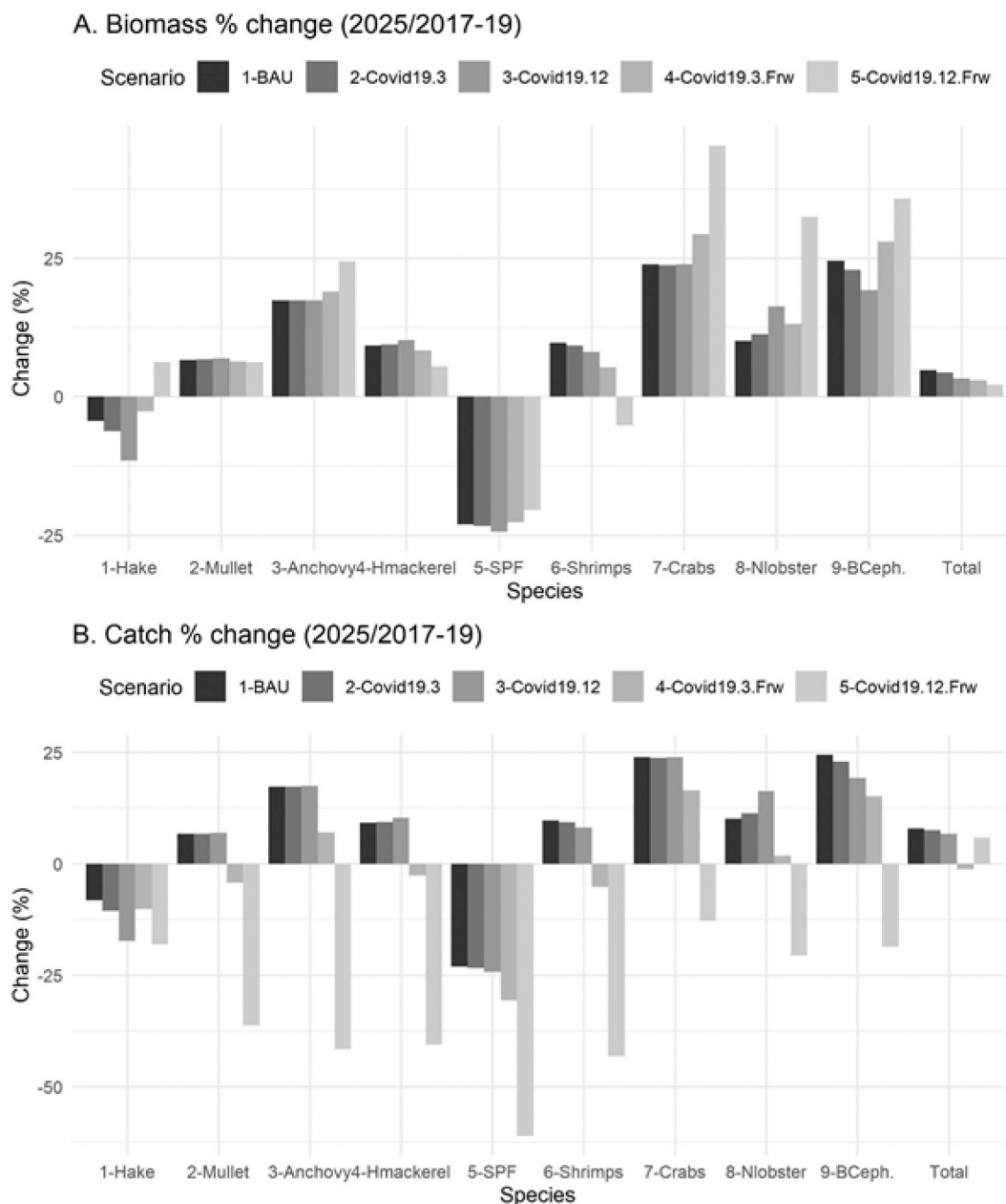


Fig. 5. Percentage (%) of change in biomass and landings of selected species and functional groups projected by the ecosystem model for 2020 and 2025 compared to 2017–2019 under 5 scenarios of fishing effort: 1-BAU, 2-COVID19/3, 3-COVID19/12, 4-COVID19/3Frw and 5-COVID19/12Frw.

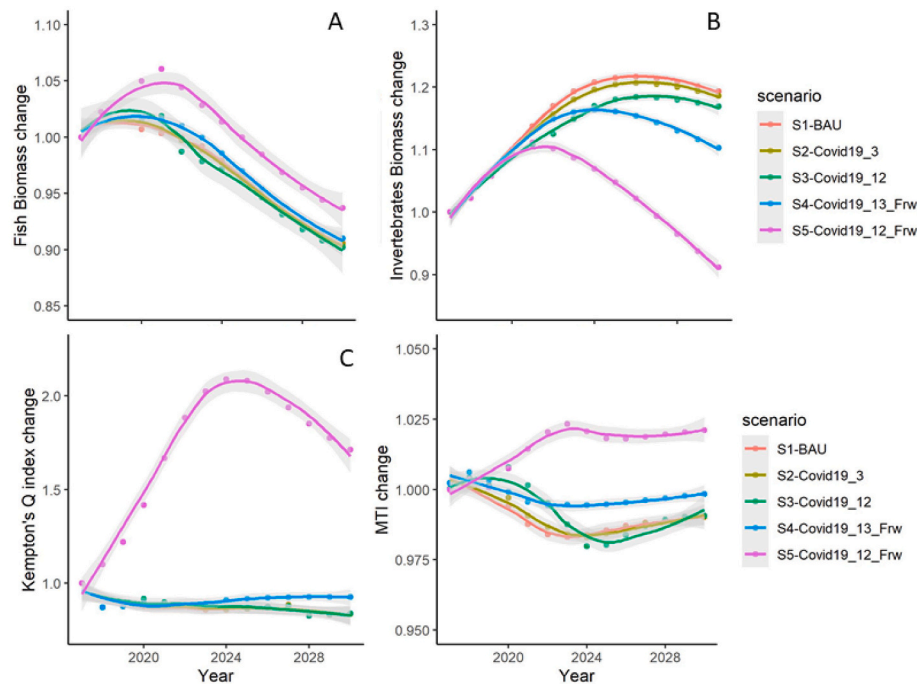


Fig. 6. Percentage (%) of change in ecological indicators projected by the ecosystem model for 2020 and 2025 compared to 2017–2019 under 5 scenarios of fishing effort: 1-BAU, 2-COVID19/3, 3-COVID19/12, 4-COVID19/3Frw and 5-COVID19/12Frw: a) Fish biomass, b) Invertebrates biomass, c) Kempton's Q biodiversity indicator, and d) MTI.

no-significant trends) and lower declines of FishB were projected, while a positive significant increase was observed for MTI, showing a slight recovery of the ecosystem structure and functioning. Nevertheless, FishB did not show a substantial change respect the rest of simulations. Ecological indicators differed the most under Covid-19/12Frw scenario: they showed significant declines in invertebrates' biomass with time, a slowdown in the decline of fish biomasses, and significant increases in ecosystem diversity and trophic complexity of catches.

4. Discussion

Results of this first in-depth study allowed us to depict direct ecological and economic implications of the COVID-19 core months of the lockdown on the fishing activity in the Catalan Sea marine ecosystem, Northwestern Mediterranean Sea (FAO, 2020b; ICATMAR, 2020a). Pre-crisis fisheries evaluations showed that the situation of several of the key targeted stocks was already of concern, in agreement with historical data and recent studies (e.g., Bas, 2009; Coll et al., 2014a; FAO, 2020b; ICATMAR, 2020a). Quantitative observations showed long-term declines of effort, landings, revenues and fisheries productivity for commercial species such as European hake, sardine, anchovy, and common octopus, in agreement with previous assessments (e.g., Coll and Bellido, 2019; Colloca et al., 2013; Colloca et al., 2017; Fernandes et al., 2017; Ramírez et al., 2021). The area had also shown increases of more resilient species under climate change and overfishing conditions (such as round sardinella, red mullets and fast-growing invertebrates) (e.g., Coll et al., 2013a; Sabatés et al., 2006).

Our "business as usual" (BAU) modelling scenario confirmed these results and projected descending trends for selected commercial species and well-tested ecological indicators, such as fish biomass, the Kemp-ton's Q biodiversity index and the Mean Trophic Level of the catch. The projected changes in indicators illustrated degradation with time (Ainsworth and Pitcher, 2006; Coll et al., 2016a; Pauly and Watson, 2005). Only the biomass of invertebrates showed a positive trend with time, in agreement with the observations. It is well described that fast-growing invertebrates can rapidly multiply due to predator and

competition release under overfishing circumstances (Coll et al., 2013a; Worm and Myers, 2003).

In this context, our study showed that the brief but intense COVID-19 fishing crisis in the first half of 2020 had at most modest recovery effect on the status of the marine resources and ecosystems in the study area. Despite the significant reductions in fishing effort during the pandemic lockdown of March to May 2020, model simulations under the S2-Covid19/3 scenario showed modest biomass increases compared to the BAU scenario. Noticeable effects were only detected for fast growing species such as shrimps and benthic cephalopods. These impacts on marine resources were not projected to have significant impacts at the ecosystem level, with ecological indicators showing similar trajectories than simulations for the BAU scenario.

These ecological model projections were overall in line with observations from the area, which only reported significant increases in landings per unit of effort for two fast growing shrimp species that most likely benefited from a decline in fishing mortality and an increase in recruitment. However, these increases could also be partially due to the effects of the intense winter storm "Gloria" that preceded COVID-19 in the study area in mid-January 2020 (Alonso et al., 2020).

The three alternative scenarios that considered larger reductions of fishing effort illustrated that to substantially recover commercial species in the study area - and ensure fisheries sustainability - a sustained and notable reduction of fishing mortality would be required. Only an average reduction with time of 34% with respect to 2019, lasting for at least 5 years, would result in noticeable changes in target species and would be translated into noticeable changes at the ecosystem level. This reduction in fishing mortality could be achieved through a combination of fishing management measures such as a net reduction of fleet effort, an increase of gear selectivity, an implementation of spatial-temporal restricted areas, and the establishment and enforcement of Marine Protected Areas. Future improvements of the ecological models can be used to select the best areas to place new protected areas, and to test their long-term ecosystem benefits. The ecological models should include seasonal fisheries data and further details on specific functional groups, and should explicitly represent species of emergent importance

such as the blue crab (which was not explicitly included in the EwE model used in this study) and update the baseline model to the latest information on illegal, unreported and unregulated catches, which can be important in the Mediterranean Sea (Coll et al., 2014b; Pauly et al., 2014).

While its ecological impacts were limited, the COVID-19 lockdown had an important impact on the fisheries sector. Economic indicators for the lockdown period showed significant decreases in fishing effort landings (15% of the annual mid captures of the period 2017–2019) and revenues (12% of the annual mid revenues). These impacts were unevenly distributed depending on fleet segment and targeted species.

According to our results, small-scale gear fisheries (SSF) were most resilient to the COVID-19 disruptions. In operational terms, most of their vessels have a small crew (usually two members), which facilitated their quick return to work once the main health concerns were clarified and solved. By June 2020, less than three months after the start of the crisis, effort, landings and revenues for SSF were already higher than in the period 2017–2019. Moreover, this was the only fleet segment that maintained higher landings during the COVID-19 lockdown in comparison to 2017 to 2019. SSF also slowed a significant increase in pre-crisis monthly landings. While SSF recovered quickly from an operational point of view, they were affected by the decrease of local fresh fish demand but less than any other fleet segment (Ortega and Mascarell, 2020), as has been observed elsewhere (Bennett et al., 2020).

Within the SSF fleet, there are relevant differences depending on targeted species. An interesting example concerns the blue crab (*Callinectes sapidus*), an allochthonous species in the study area that was firstly detected in 2012 and since has expanded exponentially (DARP, 2018a). Intensive fishing and commercialization of this new resource has been promoted by the regional government as the key instrument to control and mitigate its expansion (DARP, 2020). As a result, its landings and commercialization increased notably in the area. Specific regulation for its capture was established, and a co-management fisheries plan was put in place in 2019 (DARP 2018, 2019). Overall, blue crab landings increased from 2017 to 2019, and in 2019 this resource became the second most important species in terms of volume of small-scale fisheries catches, and the seventh in terms of value. However, during the COVID-19 lockdown, blue crab landings and EPUE declined due to the lockdown and the decline of the HORECA activity. Our preliminary analysis identify the case of the blue crab as a conservation strategy that is based on market mechanisms, and that is thus highly vulnerable to external shocks from main commercial channels.

Purse seiners and bottom trawlers were more affected by the COVID-19 crisis in terms of activity, landings and revenues, in our study area. This is in part due to the larger number of crew members needed per vessels that made the return to work more difficult for logistical and financial reasons. In addition, the quick political response to the COVID-19 crisis, such as the approval of different public support schemes designed to cover unemployment and partially compensated the sector for the decreases of fishing activity, was an enabling factor for many fishermen to stop fishing until health measures were met and minimum market conditions were ensured (BOE, 2020a, 2020b; DOGC, 2020).

It is interesting to note that those bottom trawlers that still worked in April 2020 found higher LPUEs than usual (+5%), but due to market difficulties, this increase was not translated into increases in EPUEs. This illustrates their difficulties to translate catch into monetary income due to the non-functioning market networks, as has been also illustrated with the global market (Knight et al., 2020). The situation was quite different for purse seiners, which experienced higher increases in EPUEs than LPUEs due to the high prices for sardine (mainly) and anchovy in the first weeks of April. These high prices were driven by a decrease of landings for the entire Spanish Mediterranean Sea, while simultaneously fishermen in the Spanish Cantabric region (where, in the Atlantic Ocean, is a limited TAC available) decided not to fish from March 20th to April 20th of 2020 to avoid low prices due to the low demand. This created a brief period of shortages that inflated prices for those few that remained

fishing during the COVID-19 lockdown. EPUEs dropped again in May and June once the Cantabric fleet restarted their activities and the purse-seiners activity in the Mediterranean Sea recovered, even though demand of the HORECA sector was still well below pre-COVID levels. These examples in the context of the COVID-19 crisis illustrate how complex market dynamics can interlink the operation of fisheries and condition the final revenue.

Regarding specific species, the impact of the COVID-19 crisis on landings of main commercial fish and invertebrates resulted in a general decrease of landed volumes in comparison to 2017 to 2019. As previously discussed, some species showed declining landing even before COVID-19, thus acute declines observed during the lockdown cannot be fully attributed to the health crisis. Of especial interest for its commercial value and its conservation concern is European hake, a highly exploited or overexploited species in the Mediterranean Sea (FAO, 2020b), which has been listed in the Vulnerable (VU) category of the regional IUCN Red List of Threatened Species (Abdulla et al., 2008; Di Natale et al., 2011). Hake epitomizes the consequences of the COVID-19 crisis on stocks characterised by long-term decreases in landings, associated with a poor stock status and a sustained high fishing pressures on recruitment (ICATMAR, 2020a, 2020b). In the case of hake, a very significant decrease in monthly landings was already observed in the months of 2020 prior to the COVID-19 lockdown in comparison to 2017–2019 volumes. The volume of landings during the COVID-19 lockdown did not decrease substantially due to the increase in LPUE for those vessels that remained active. This paradox suggests that the current overcapacity of the system and the poor status of hake stock is enough to ensure the almost same low amounts of captures with a much-reduced fishing activity.

5. Conclusions

In this paper we analysed the immediate ecological and economic implications of the COVID-19 lockdown on mixed small-scale and semi-industrial fisheries in the northwestern Mediterranean Sea. Our study provides some insights that may be useful for the future of fish management and environmental conservation policies in the study area: (1) environmental status improvements require structural long-term management commitments - and in our specific case study, major fishing mortality reductions -; (2) short-term cessations such as the one provoked by COVID-19 lockdown early 2020 cannot recover marine resources and the ecosystem; (3) short-term, small-scale fishing gears seems to be more resilient to abrupt short-lived crisis than other fleet segments because they have proved to be more flexible; and (4) external market shocks may lead to problematic situations when conservation measures depend exclusively on market dynamics (as highlighted by the example of the blue crab). Resilient conservation mechanisms that rely on the market as the main driver must be made resilient through safeguards mechanisms in case markets fail.

At the time of writing, the COVID-19 health pandemic is far from over and there are uncertainties about its future evolution. This may mean that incipient economic recovery since the COVID-19 lockdown may be temporary or can be reversed through plausible future tightening of restrictions related to mobility and fluctuations in seafood demand from HORECA channel and tourism. Marine fisheries will thus remain vulnerable to resurgences in COVID-19 infection rates and the long-term fisheries recovery from the 2020 COVID-19 disruptions are unclear. The 2020 lockdown will have likely high long-term economic impacts (Banco de España, 2020), which may lead to a further decrease in demand for fresh fish, especially on higher-valued products in the HORECA channel. At the same time, the perspective of a global slowdown of the economic recovery may lead to continued low prices of some of the intermediate expenses of fishing activities, such as oil prices, which can soften the economic burden on the fleet. The COVID-19 crisis has already resulted in a major reduction in oil consumption worldwide, which has decreased oil prices up to the present day. Overall,

preliminary data shows that COVID-19 crisis produced revenue losses in the Mediterranean fisheries sector, but they were cushioned by the reduction of operative costs and the deployment of an extensive network of public aid to the sector (Ortega et al., 2020).

At the political and management level, high uncertainties remain, too. A persistent economic crisis may increase the risk of slowing down or lowering expectations about the implementation of stock recovery measures to increase fishing sustainability in the area, such as the Multiannual plan for the fisheries exploiting demersal stocks in the western Mediterranean Sea (EU, 2019). With a mid-term perspective, if the economic results of the fishing sector further deteriorates, the private sector may reduce its investment capacity, which in turn will hamper efforts to introduce operative changes needed to decrease its ecological impact and ensure sustainability, such as reducing overcapacity, increasing selectivity of fishing activities, reducing discards, avoiding by-catch of vulnerable species and reducing impact on essential habitats.

It is thus clear that additional studies are needed to further evaluate the impacts of the COVID-19 into marine fisheries to achieve a comprehensive understanding of the long term consequences of the pandemic, and to establish resilient long-term solutions for the fisheries, resources and ecosystems of the Northwestern Mediterranean Sea.

Declaration of competing interest

The authors declare that they do not have any conflict of interest with the results presented in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2021.108997>.

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