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Spatio-temporal trends of the bottom trawling activity in a mud volcano field of the north-eastern Gulf of Cádiz (south-western Iberian Peninsula)

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ABSTRACT

Multi-species bottom trawl fisheries are one of the human activities with a great impact on the benthic habitats and their associated biota. This study provides estimates of the bottom trawling activity (effort), catches and landings of the main commercial species as well as an estimation of the total revenue (TR) generated inside a mud volcano field located in the Spanish margin of the Gulf of Cádiz, during a time series from 2007 to 2012. To date, no studies have been carried out to analyse the temporal evolution of bottom trawling activity and TR in a mud volcano fied, or the economic consequences of possible potential bottom trawling regulation of certain sectors harbouring vulnerable and/or threatened habitats. In this study, Vessel Monitoring System data, logbooks and sales slips were used. The spatial distribution of the bottom trawling activity, catches and TR were related to the seafloor morphology and specific bottom types of the mud volcano field. During the time series, a high bottom trawling activity and associated catches was detected in flat sandy and muddy bottoms, including the Anastasya sector and between the Guadalquivir and Cádiz Diapiric Ridges. Low bottom trawling activity and catches were detected in the deepest areas but also in areas with hard and detritic bottoms such as Gazul and Chica sectors as well as in the Diapiric Ridges. A similar spatial pattern was detected for the TR associated with these bottom trawling fisheries. An increase in bottom trawling activity was detected during the time series, mainly at the end, probably for increasing the TR and mantaining the economic profit due to the instability and increases in fuel prices and offset the increased costs. Based on the obtained information, bottom trawling regulations should be implemented in certain sectors harboring singular and/or threatened habitats and species. In some of these sectors, a low TR from bottom trawling was detected and, bottom trawling regulation may potentially have a low socioeconomic impact. This specific bottom trawling regulation could provide a sustainable balance between bottom trawling activities and habitat conservation in this mud volcano field according to the aims of the Habitats Directive (92/43/EEC) and the European Marine Strategy Framework Directive (2008/56/EEC).

1. Introduction

During the last decades the increase of anthropic activity in some areas of the ocean has led to increased cumulative pressures on some marine ecosystems, affecting different habitats and their associated communities (Halpern et al., 2008; Duarte, 2014). Hydrocarbon extraction, seabed mining and fishing are some of the main threats to marine biodiversity, both in Marine Protected Areas and unprotected areas (Gray, 1997; Thompson et al., 2018; Mazaris et al., 2019). Advances in the technology of some marine anthropic activities have improved their efficiency and have allowed humans to exploit deeper areas, representing one of the main threats for deep-sea marine biodiversity (Costello et al., 2010; Mazaris et al., 2019). Different analyses on the cumulative anthropic pressures in different areas of the world have

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been done using maps of the spatial distribution of different types of anthropic activities (Halpern et al., 2008, 2015; Korpinen et al., 2012; Tournadre, 2014). These maps generally help to manage the spatial use of human activities in different marine ecosystems and ecologically important areas through an efficient marine spatial planning (Stelzenmüller et al., 2008; Le Pape et al., 2014; Andersen et al., 2018). The new global challenge is to achieve a sustainable management of the human activities in the marine environment through an ecosystem approach, and in this sense is important to have accurate information on the spatial distribution of the human pressures as well as of the threatened and vulnerable habitats and species.

The consequences of bottom trawling have been extensively studied and, nowadays, this type of fisheries represents one of the most important human pressures in the marine environment, causing serious impacts on its habitats and associated biota (Jones, 1992; Kaiser and Spencer, 1996; Kaiser et al., 2003; Worm et al., 2006). Habitat destruction, sedimentary changes in the seabed, structural changes in populations of commercial and non-commercial species and the direct collapse of both the fishing grounds and some slow-growing species are some of the problems caused by continuous bottom trawling (Jones, 1992; Jackson et al., 2001; Baum et al., 2003; Pauly, 2003; Oberle et al., 2016). In addition, the frequency and intensity of the bottom trawling activity together with the types of habitats and communities in one specific area are important for determining the resilience and recovery time of the ecosystem (Queirós et al., 2006; Hiddink et al., 2017; Clark et al., 2019). Currently, in several areas of the European Union (EU) there are gaps on the consequences of the bottom trawling on the various components of the marine ecosystem (Van Denderen et al., 2015). This is because mapping some types of fisheries and habitats is difficult, and also because some habitats are more studied than others, and the marine ecosystems generally evolve under many interconnected pressures that are often studied separately and not as a whole, among other constrains (Ban et al., 2010; Halpern et al., 2015). Thus, the EU countries are implementing the Marine Strategy Framework Directive (MSFD) (Directive, /56/EEC, 2008), which requires EU member States to study the different pressures and impacts on the marine ecosystem in order to analyse its environmental status under an ecosystem-based approach. The final aim is to maintain and preserve the biodiversity of marine ecosystems and to develop a sustainable management of marine resources through marine spatial planning, while maintaining a Good Environmental Status (GES) of the ecosystem. In addition, a balance in the exploitation of marine resources and their management, often complex and conflicting, could generate greater acceptance by society and facilitate the implementation of future fisheries management plans, ensuring the economic viability of fishing activities and market supply (Nielsen et al., 2018). The MSFD, in combination with the Water Framework Directive (WFD), the Natura 2000 Network and the Habitat Directive (Directive 92/43/EEC), aims to mantain Special Areas of Conservation to ensure the habitats sustainability and their resources with human activities (Directive, /56/EEC, 2008; Van Hoey et al., 2010; De Vivero et al., 2012).

The Gulf of Cádiz (GoC) represents an area with a high hydrological, geological and biological complexity due to its location between two continents (Europe and Africa) and two basins (Atlantic Ocean and Mediterranean Sea) (Pinheiro et al., 2003; León et al., 2007; Medialdea et al., 2009; Rueda et al., 2012a, 2016; Cunha et al., 2013; Delgado et al., 2013; Díaz-del-Río et al., 2014; Sánchez-Leal et al., 2017). From a socio-economic point of view, this area presents a high diversity of commercial species that are exploited by different types of fisheries (Sobrino et al., 1994; Silva et al., 2002; Jiménez et al., 2004; Vila et al., 2010; Pita et al., 2015; Bueno-Pardo et al., 2017). The north-eastern GoC supports an important fishing activity that includes a total of 761 fishing vessels (*ca.* 56% of the Andalusian fishing fleet) as well as important fishing harbours in Huelva, Isla Cristina, Ayamonte and Sanlúcar de Barrameda, which provide a large number of job opportuinities (Junta de Andalucía, 2020). In this area, the bottom trawling fleet is one of the most important ones with 125 trawling vessels (*ca* 16% of the north-eastern GoC fishing fleet and *ca.* 9% of the total Andalusian fishing fleet) (Junta de Andalucía, 2020). Unfortunately, bottom trawling may produce perturbation on the seabed and, therefore, on different habitats, including some vulnerable and threatened ones of the Habitats Directive 92/43/EEC (*e.g.* Habitats 1170 and 1180 from the Habitats Directive) and of International Conventions (*e.g.* OSPAR) (*e.g.* sea-pen and burrowing megafauna communities, carbonate mounds, coral gardens, *etc.*) (Díaz-del-Río et al., 2014; González-García et al., 2020b). Some of these habitats have been detected in different sectors of a mud volcano field that was recently proposed as the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" to the EU Natura 2000 network (Díaz-del-Río et al., 2014; Rueda et al., 2012a; b, 2016; González-García et al., 2020b; Lozano et al., 2020b; Urra et al., 2020).

The bottom trawling fishery of the north-eastern GoC is multi-species (Sobrino et al., 1994; Jiménez et al., 2004) and the biology of some of the commercial species has been studied (Jiménez et al., 1998; Silva et al., 2002; Baldó et al., 2006; Vila et al., 2010, 2013). Most of the fleet operating in the area mainly targets the shallowest fishing grounds outside the SCI (González-García et al., 2020a). Nevertheless, some of the deepest (and most remote) fishing gounds of the Norway lobster (*Nephrops norvegicus* (Linnaeus, 1758)) and the deep-water rose shrimp (*Parapenaeus longirostris* (Lucas, 1846)) are located inside the SCI (Fig. 1A), and are exploited by some bottom trawling vessels (Ramos et al., 1996; Díaz-del-Río et al., 2014; González-García et al., 2020a). These trawlers target these crustaceans of high commercial interest together with other species like the European hake (*Merluccius merluccius* (Linnaeus, 1758)) and the blue whiting (*Micromesistius poutassou* (Risso, 1827)), the latter as by-catch (Sobrino et al., 1994; Ramos et al., 1996; Jiménez et al., 2004; González-García et al., 2020a). This seems to cause some impact to sensible habitat-forming species (*e.g.* sea-pens) but this impact still needs to be evaluated in detail (González-García et al., 2020b; Lozano et al., 2022 in prep.). A detailed study of the spatial-temporal trends of the bottom trawling activity, catches and associated total revenue (TR) in the SCI would improve management measures for conserving some vulnerable and/or threatened habitats with the lowest socio-economic consequences for fishermen.

The main aim of this study is to combine spatial distribution maps of bottom trawling activity (effort) and landed catches data throughout a time series of six years in order to estimate the TR in the SCI and in some sectors harbouring vulnerable and/or threatened habitats within the SCI that may be considered for a potential specific bottom trawling regulation. Therefore, the main objectives are related: i) to analyse the spatial and temporal changes of the bottom trawling activity and associated catches in the SCI "*Volcanes de fango del golfo de Cádiz*"; ii) to estimate the total revenue from the landed catches of the SCI and of different sectors harbouring vulnerable and/or threatened habitats within the SCI; and iii) to detect those fishing harbours with the largest total revenue from the SCI and the different sectors. The latter point is crucial for obtaining a preliminary view of the impact to fishermen from different harbours if new potential bottom trawling regulations are applied in those sectors of the SCI that harbour vulnerable and/or threatened habitats included in EU Directives and International Conventions. The starting hypothesis is that different sectors of the SCI are exposed to different trawling activity due to their different environmental characteristics and this may generate different total revenue derived from the bottom trawling activity and the catches of the different commercial species.

2. Material and methods

2.1. Study area

The present study has been carried out in the shallowest and northern most part of the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" (ESZZ12002), which is located in the north-

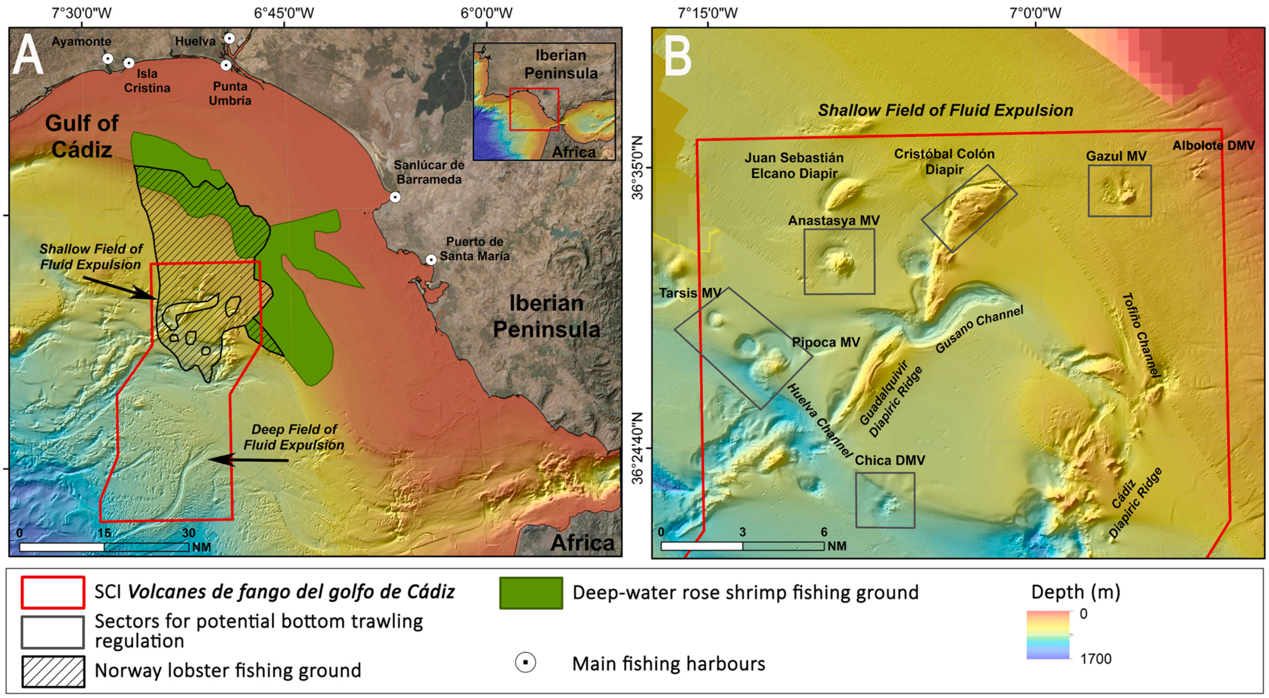

Fig. 1. A) Location of the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" with indications of the *Shallow and Deep Fields of Fluid Expulsion* and the main fishing harbours as well as the main fishing grounds for the bottom trawling fleet (the Norway lobster and the deep-water rose shrimp) (data on fishing grounds obtained from Ramos et al., 1996). B) The Shallow Field of Fluid Expulsion with proposed sectors (polygons) for potential bottom trawling regulation because containing threatened and vulnerable habitats listed in EU Directives and International Conventions according to previous studies on habitats and benthic communities of the SCI (Díaz-del-Río et al., 2014; Rueda et al., 2012a; b, 2016; Palomino et al., 2016; González-García et al., 2020a; b; Lozano et al., 2020b; Urra et al., 2020).

eastern Gulf of Cádiz (GoC) as well as in the ICES Division IXa and the OSPAR Region IV. This shallow part of the SCI contains a mud volcano (MV) field, also known as "Shallow Field of Fluid Expulsion" (SFFE), which spans from the upper to the middle slope of the south-western continental margin of the Iberian Peninsula (300–800 m depth) (Fig. 1A) (Díaz-del-Río et al., 2014; Palomino et al., 2016; . González-García et al., 2020b).

The wide continental shelf of the north-eastern GoC and the different environmental features such as the seabed complexity, the nutrient inputs resulting from the outflow of important rivers (*e.g.* Guadalquivir and Guadiana) as well as the mixing of water masses and species from the Mediterranean Sea and the Atlantic Ocean that converge here, among others, favour a high diversity and productivity of different commercial species and therefore of several fishing grounds where a multi-species fishing fleet operates (Sobrino et al., 2002; Catalán et al., 2006; Delgado et al., 2013; Díaz-del-Río et al., 2014).

On the continental slope, where the SCI is located, the contourite drift deposits are intercalated with numerous MVs such as Gazul, Anastasya, Tarsis and Pipoca, two mud volcano-diapir complexes (DMV) (Albolote and Chica), some diapirs (*e.g.* Cristóbal Colón, Juan Sebastián Elcano), carbonate mounds, diapiric ridges (Guadalquivir and Cádiz Diapiric Ridges) and different seafloor depressions and channels (*e.g.* Gusano, Huelva, Tofiño) eroded by the Mediterranean Outflow Water (MOW) current (Fig. 1B) (Díaz-del-Río et al., 2014; Palomino et al., 2016; Sánchez-Leal et al., 2017; Lozano et al., 2020b). In addition, the presence of numerous fields of Methane-Derived Authigenic Carbonates (MDACs) (*e.g.* at Gazul and Pipoca MVs, Chica DMV, *etc.*) favour the presence of a high diversity of habitats and species in specific sectors of the SCI (Díaz-del-Río et al., 2014; Palomino et al., 2016; Rueda et al., 2016; Lozano et al., 2020b; González-García et al., 2020b; Urra et al., 2020).

Studies on the presence of chemosynthesis-based communities with chemosymbiotic species that are endemic of the GoC (related to Habitat 1180, "Submarine structures made by leaking gases" of the Habitat Directive), cold-water coral reefs and aggregations of deep-sea sponges, gorgonians and antipatharians (related to Habitat 1170 "Reefs" of the Habitat Directive), together with other studies on the high diversity of sponges, bryozoans or molluscs (with new species to science) have indicated that the SCI may represent a biodiversity hotspot for the European margin (Rueda et al., 2012a; b, 2016; Díaz-del-Río et al., 2014; Sitjà et al., 2018; Lozano et al., 2020b; González-García et al., 2020b; Ramalho et al., 2020; Utrilla et al., 2020; Urra et al., 2020). Some of these habitats and species are currently impacted by the bottom trawling fleet that operates in the SCI due to the important Norway lobster and the deep-water rose shrimp fishing grounds (González-García et al., 2020a; b; Lozano et al., 2020a). This is why different ecologically important sectors have been proposed for bottom trawling regulation in previous studies in order to protect these habitats from this destructive fishing technique (Rueda et al., 2012a; b, 2016; Díaz-del-Río et al., 2014; Lozano et al., 2020b; González-García et al., 2020b; Urra et al., 2020). Therefore in order to improve the protection of these habitats in the future Special Area of Conservation (SAC) (once Management Plans will be established for this SCI), different sectors of exclusion to bottom trawling were proposed in the final report of the INDEMARES Project as well as in different scientific papers (Rueda et al., 2012a; b, 2016; Díaz-del-Río et al., 2014; Palomino et al., 2016; González-García et al., 2020b; Urra et al., 2020) due to the presence of endemic chemosymbiotic species (*e.g.* bacterial mats, *Solemya elarraichensis* P.G. Oliver, Rodrigues & Cunha, 2011; *Lucinoma asapheus* P.G. Oliver, Rodrigues & Cunha, 2011, among others) and vulnerable habitats with a high diversity of sensitive habitat-forming species (habitat 1170, habitat 1180, sea-pen and bamboo coral communities, gorgonian and sponges aggregations, among others) (Fig. 1; Table S1 supplementary material). All these proposed sectors occupy an area that represents approximately 11% of the total area of the SFFE included in this SCI.

2.2. Bottom trawling activity, landed catches of the main commercial species and associated total revenue

Data from the Vessel Monitoring System (VMS) and the logbooks of the different fishing vessels from January 2007 to December 2012, provided by "*Secretaría General de Pesca*" of the Spanish Government, were used for analyzing the spatial distribution of the bottom trawling activity and the provenance of the landed catches of the different commercial species of the bottom trawling fleet operating in the SCI.

The analyses were carried out with the free software package VMStools for R (Hintzen et al., 2012) and the results obtained were represented with ArcGis v10. The VMS data contained date, time, vessel registration number and position, speed and course, among other data. Those VMS records that were duplicated, with insufficient number of signals or those located outside the study area were not considered during the analysis (Lee et al., 2010; Hintzen et al., 2012). Then, the method based on the speed profile was used for identifying the positions where the vessel was trawling (Bastardie et al., 2010a; Hintzen et al., 2010). In this method, the average speed of the vessel between successive signals is calculated considering the time interval and the euclidean distance between successive signals, so a frequency distribution of average speeds was finally obtained (Hintzen et al., 2012). Finally, records with speed frequencies between 2 and 5 knots were identified as those indicating "fishing" and these records were linked to the landings of commercial species of that fishing vessel during that day. Although other studies suggest that trawling vessels operate at different speed ranges during bottom trawling (2–8 knots, Mills et al., 2007; 2–4 knots, Bueno-Pardo et al., 2017), knowledge of the fishing fleet and data provided by fishery observers in the study area were also taken into account for the assignment of the average effective trawling speed frequencies. Therefore, any record of vessel speed occurring outside this range (<2 and >5 knots) was not identified as "fishing".

In order to know the spatial distribution and temporal evolution (2007–2012) of the landed catches of different commercial species (hereafter named as catches), the VMS data points indicating "fishing" were linked to the logbooks data through a common identifier created for this purpose at the midpoint of each fishing operation during each daily trip for estimating the provenance of those landed catches. All the resulting data (number of fishing operations and trips per vessel, number of hours of trawling activity, catches, *etc.*) were transferred to GIS and were rasterised for creating maps. The study area was divided in 1 Km^2 grid cells and the resulting data was added for displaying the results, per 1 Km^2 grid, of the distribution of the bottom trawling activity as well as the catches of the main commercial species. The raster data of bottom trawling activity and catches were considered for obtaining raster data on the spatial distribution of the catches (Tonnes, t) Per Unit of Effort (hours) (LPU).

Data on catches of different fishing vessels were also used for estimating the landings at the most important fishing harbours located in the north-eastern GoC. Because many of the catches of the GoC bottom trawling fleet are identified with generic codes (*e.g.* LOX: Reptantia; FIN and MZZ, Osteichthyes; SKA, Raja spp.; AXR, Aristeus spp.; CRA, Brachyura, *etc.*), some data had to be grouped for better understanding of these landings of species that generally had very low values within the SCI. The groups made were Red shrimp group (RSH), Prawn group (PRA), Monkfish group (MON), Cephalopods group (CEP), Elasmobranchs group (ELA), Other fishes group (OFI) y Other crustaceans group (OCR) (Table S2, supplementary material).

For estimations of the total revenue (TR) associated with the catches of the different commercial species, the data provided in 2020 by the Andalusian Information System on Marketing and Fish Production Data of the "*Dirección General de Pesca y Acuicultura de la Junta de Andalucía*" (IDAPES) were used (Table S2 supplementary material). The data included sales notes of the landed species at the fish market, including data on weight (Tonnes) and the monthly average price per kilogram (€/kg) of the species auctioned (or groups of species) during each year of the time series (2007–2012) (Table S2). The TR was calculated by linking the catches of each species in grid cells of 1 km^2 within the SCI with the average price per kilogram of those species in that year at the landed harbours. Estimations of the TR from the groups of species with low catches (*e.g.* RSH, PRA, *etc.*) were calculated from (1) the TR of each of the species of that group using the average annual price multiplied by the total catch of that species during the same year and (2) the sum of the TR of each species of that group in that particular year (Table S2). Estimates of the TR were then calculated for each 1 Km^2 grid cell (sumatory of the revenue for each species in the 1 Km^2 cells). Later on, these data were transferred to GIS in order to obtain different spatial distribution maps of the TR per unit of effort in 1 Km^2 grid cells located inside and outside the mud volcano field of the SCI. Finally, the TR coming from the SCI or the proposed sectors for bottom trawling regulation was calculated at each harbour during each year by multiplying the catches of the different species (or groups of species) coming from those sectors with the average price of the same species in that year. This was done in order to know which harbours will be affected if bottom trawling regulation will be applied.

3. Results

3.1. Bottom trawling activity and catches of the main commercial species

The results obtained in the present study provide estimates of the total bottom trawling activity (also interpreted as bottom trawling effort) and catches (based on Vessel Monitoring System, VMS, and logbook data) in 1 km^2 grid cells for all trawling vessels that fished in each grid cell within the the Site of Community Importance (SCI) during each year of the time series (2007–2012). Therefore, the bottom trawling activity values are much higher than those published by González-García et al. (2020a) who displayed the average bottom trawling activity and catch per trawling vessel in 1 km^2 cells for the year 2011. During the time series (2007–2012), bottom trawling activity showed a spatial decrease in intensity from the continental shelf to the slope, where the Shallow Field of Fluid Expulsion (SFFE) of the SCI is located (Fig. 2). In general, an average of 51 bottom trawling vessels operated in the SFFE of the SCI during the time series. The number of trawling vessels inside of the proposed sectors was generally lower than those of vessels outside of the sectors, with Gazul sector displaying a low number of trawling vessels throughout the time series (average of *ca.* 2–3 trawling vessels during 2007–2012), in contrast to Anastasya sector where a high number of trawling vessels was detected (average of *ca.* 28 trawling vessels) (Table 1).

During the time series, the spatial trend of bottom trawling activity remained relatively constant with high activity outside the SCI, mainly in the shelf and also in the upper slope (Fig. 2). In the SFFE of the SCI, bottom trawling ativity was especially high in flat sedimentary areas around the Guadalquivir Diapiric Ridge, mainly affecting Anastasya and Cristóbal Colón (located close to Anastasya) sectors and, to a lesser extent, Tarsis and Pipoca sector (Fig. 2). Bottom trawling activity was low to very low at Guadalquivir and Cádiz Diapiric Ridges, at Gazul and Chica sectors and at depths greater than 700 m (Fig. 2).

The total number of bottom trawling hours in the SFFE per year was low for 2007 and high for 2009 and 2012, respectively, showing a fluctuating increase in periods of every 3 years (Table 1). Nevertheless, Anastasya and Cristóbal Colón sectors generally showed the highest number of bottom trawling hours during the time series, especially in 2009 and 2012 respectively (Table 1). In Tarsis and Pipoca sector, an intermediate number of bottom trawling hours was detected during the time series, with an increase in 2011 and 2012 (Table 1). Finally, Chica and Gazul sectors generally showed very low number of bottom trawling hours during the time series, with minima in 2008 and 2012, respectively (Table 1).

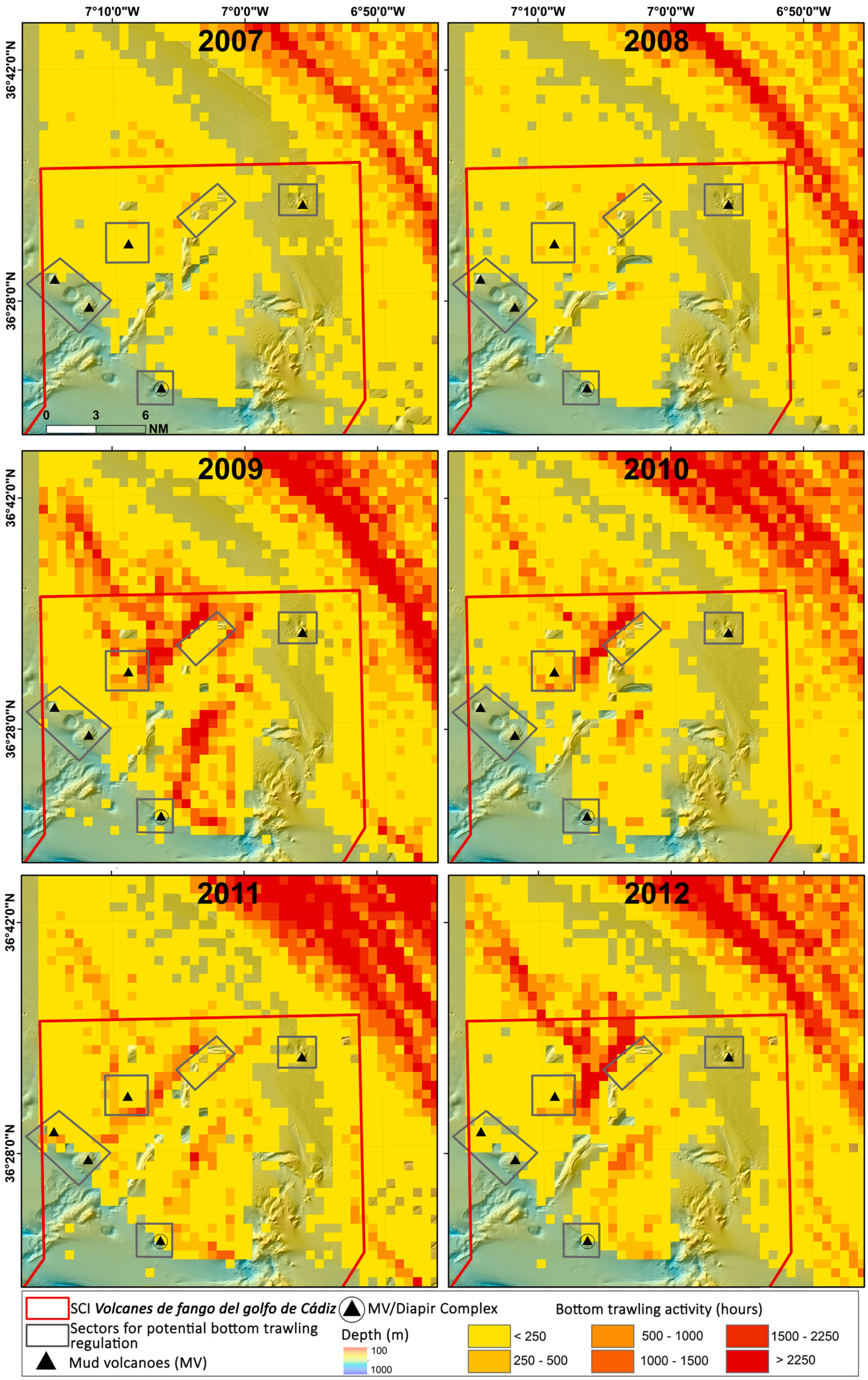

Fig. 2. Spatial distribution and temporal changes of the bottom trawling activity (effort) (total number of bottom trawling hours) in 1 km^2 grid cells in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*", including the different sectors proposed for potential bottom trawling regulation in previous studies (see Fig. 1. and Table S1), and the adjacent shelf and slope of the Spanish margin of the Gulf of Cádiz.

Table 1
Bottom trawling activity (effort), including the number of trawling vessels and total bottom trawling hours of all trawling vessels per year, in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" and in the different sectors proposed for bottom trawling regulation according to Fig. 1 and Table S1 (Supplementary material).

	SCI		Gazul		Cristóbal Colón		Anastasya		Tarsis and Pipoca		Chica	
	Hours	Vessels	Hours	Vessels	Hours	Vessels	Hours	Vessels	Hours	Vessels	Hours	Vessels
2007	34624	42	4	2	358	7	2311	21	416	9	36	4
2008	43998	45	5	2	726	12	2071	18	122	6	14	2
2009	267036	58	4	3	3431	23	11824	38	224	7	171	10
2010	114478	55	7	1	2483	21	6317	29	5	2	87	4
2011	126928	54	15	5	1765	22	8307	34	2841	20	536	9
2012	180820	49	0	0	3960	18	4021	26	1066	12	174	9

3.2. Spatial distribution and temporal changes of catches of the main commercial species

The main commercial species caught in the SCI was the deep-water rose shrimp (DPS) with an average of 86.59 Tonnes (t) per year (*ca.* 6% of the total catch of this species in the north-eastern GoC), but displayed large fluctuations during the time series (maxima in 2009 and minima in 2007, Table 2). The Norway lobster (NEP) was the second most caught species in the SCI with an average of 30.43 t per year (*ca.* 32% of the Norway lobster total catch in the north-eastern GoC), with maxima in 2009 and minima in 2007 (Table 2). The European hake (HKE) was the third most caught species in the SCI with an average of 17.11 t (*ca.* 5% of the European hake catch in the north-eastern GoC), with maxima in 2010 and 2011 and minima in 2007. Other important commercial species caught in the SCI are the Osteichthyes (OST group) with an annual average of 26.89 t during the time series, followed by the monkfishes (MON group) with an average of 9.4 t and the elasmobranchs (ELA group) with an average of 4.56 t (Table 2).

Considering all proposed sectors for a potential bottom trawling regulation (combining data of Gazul, Cristóbal Colón, Anastasya, Tarsis/Pipoca and Chica sectors), the total catches represented an average of 9% of the total catches in the SCI, with minima in 2009 (7.5% of all catches in the SCI) and maxima in 2011 (10.7%, Table 3). The catches of commercial species from all these proposed sectors were maximal in 2009 (24.98 t) and 2011 (26.91 t) and minimal in 2007 and 2008 (*ca.* 10.5 t) (Fig. 3, Table 3). The most caught commercial species considering all proposed sectors were the deep-water rose shrimp, followed by the Norway lobster and the European hake. Thus, for 2011 and all proposed sectors, the catch of the deep-water rose shrimp was 14.12 t (10.99% of the total catch of this species within the SCI and 1% of the total catch of this species in the north-eastern GoC in 2011), followed by the Norway lobster with 4.01 t (12.24% of the total catch of this species within the SCI and 5% of the total catch of this species in the north-eastern GoC in 2011) and the European hake with 2.58 t (10.97% of the total catch of this species within the SCI and 1% of the total catch of this species in the north-eastern GoC in 2011) (Table 3).

Table 2
Total annual catches (Tonnes, t) (based on VMS and logbook data) of the main commercial species and groups of commercial species (Table S2, supplementary material) caught by the bottom trawling fleet in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" during 2007–2012. NEP: *Nephrops norvegicus*; DPS: *Parapenaeus longirostris*; HKE: *Merluccius merluccius*; WHB: *Micromesistius poutassou*; RSH group: Red shrimp; OST group: Osteichthyes; PRA group: Prawn; MON group: Monkfish; CEP group: Cephalopods; ELA group: Elasmobranchs; OFI group: Other fishes; OCR group: Other crustaceans.

	2007	2008	2009	2010	2011	2012
NEP	20.91	25.45	43.60	28.85	32.80	30.99
DPS	11.40	41.65	187.09	49.71	128.55	101.13
HKE	7.40	9.88	21.36	23.15	23.47	17.38
WHB	14.87	12.01	4.16	62.63	5.62	3.29
RSH	0.09	0.07	0.40	0.22	2.06	1.67
OST	31.71	24.38	41.83	21.23	23.44	18.73
PRA	1.81	1.35	15.99	3.41	0.44	0.14
MON	4.46	4.61	4.56	4.20	5.82	3.74
CEP	2.77	3.00	1.72	4.57	12.57	16.11
ELA	8.46	5.08	8.31	4.11	2.92	7.21
OFI	2.43	3.85	5.88	3.69	4.98	2.47
OCR	0.11	0.23	0.74	0.93	8.40	1.74

Regarding each proposed sector separately, the largest catches were concentrated in those sectors with high bottom trawling activity (Table 4, Fig. 3). Thus, Anastasya sector presented the largest catches with an average total catch per year of 10.96 t (5.38% of the total catch within the SCI), with the deep-water rose shrimp being the most caught species, followed by the Norway lobster and the European hake (Table 4). An increase in total annual catches was observed in this sector at the beginning of the time series (17.44 t in 2009), followed by a decrease at the end (7.57 t in 2012, Table 4). Cristóbal Colón sector is the second one in terms of catches with an average catch per year of 3.53 t (1.69% of the total catch within the SCI), displaying maxima in 2010 (5.37 t) and minima in 2007 and 2008 (1.48 t, Table 4, Fig. 3). Chica and Gazul sectors (with low to very low bottom trawling activity) displayed the lowest annual catches, which generally represented less than 1% of the total annual catch for the whole SCI in any of the years of the time series (Table 4, Fig. 3).

Fig. 4A displays the evolution of the total annual landed catches (Tonnes, t) Per Unit Effort (hours) (LPU) in the SCI during the time series 2007–2012, highlighting the low LPU values that are maintained in all the proposed sectors combined, with maxima in 2009 (18% of the LPU for the whole SCI) and minima in 2012 (10%). Nevertheless, the largest difference between the LPU for all sectors combined and the LPU for the SCI was detected in 2007 (6%) (Table S3). Regarding each of the proposed sectors separately, Tarsis and Pipoca sector displayed the largest average LPU (0.18 t per hour, with, maxima in 2008 and minima in 2007), followed by Cristóbal Colón sector (0.16 t per hour, with maxima in 2007 and 2010 and minima in 2011 and 2012). The minimum LPU values were generally observed in Gazul (mostly in 2010 and 2012) and Chica (mostly in 2007 and 2012) sectors (Table S3). Fig. S1 (supplementary material) displays the spatial distribution of LPU per 1 km^2 grid cells during the time series. The largest LPU values were concentrated in areas generally located outside the proposed sectors for potential bottom trawling regulation, especially in the westernmost part of the SCI (north and westwards Anastasya sector).

3.3. Total revenue of the caught commercial species

Considering the catches of all commercial species combined, the estimations of the total revenue (TR) were high around the Guadalquivir Diapiric Ridge (eastwards and westwards) as well as at Anastaysa and Cristóbal Colón sectors (Fig. 5). On the contrary, the TR was low at the Guadalquivir and Cádiz Diapiric Ridges, the contouritic channels and Gazul and Chica sectors (Fig. 5).

The main species responsible for the TR were the deep-water rose shrimp and the Norway lobster. The TR associated with these two decapods, compared to the remaining commercial species within the SCI, contributed from 65% in 2007 to 82% in 2012. The maximum TR

Table 3
Total annual catches (Tonnes, t) (based on VMS and logbook data) and percentages of catches (%) of main commercial species in all the proposed sectors for potential bottom trawling regulation in relation to the total landed catches of the entire Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*". during 2007–2012. NEP: *Nephrops norvegicus*; DPS: *Parapenaeus longirostris*; HKE: *Merluccius merluccius*; MON: Monkfish group; OTR: Other fishes and crustaceans species (WHB: *Micromesistius poutassou*; RSH group: Red shrimp; OST: Osteichthyes group; PRA: Prawn group; CEP: Cephalopods group; ELA: Elasmobranchs group; OFI: Other fishes group; OCR: Other crustaceans group).

	2007		2008		2009		2010		2011		2012	
	t	%	t	%	t	%	t	%	t	%	t	%
NEP	1.79	8.57	2.30	9.05	3.52	8.08	2.66	9.22	4.01	12.24	2.47	7.97
DPS	1.46	12.77	2.86	6.87	12.75	6.82	4.10	8.24	14.12	10.99	7.19	7.11
HKE	0.66	8.88	0.95	9.57	1.72	8.04	2.01	8.7	2.58	10.97	1.62	9.33
MON	0.35	7.77	0.27	5.75	0.38	8.31	0.31	7.36	0.60	10.36	0.23	6.23
OTR	6.30	10.12	4.09	8.18	6.60	8.36	11.41	11.32	5.60	9.26	5.02	9.78

associated with these two species was detected in 2009 for the SCI, but represented a much lower value than that for the continental shelf where catches are generally much higher (Table 4, Fig. 5).

Considering all sectors combined, the TR represented an annual average of 133000 € per year during the time series, with minima in 2007 and 2008 (with *ca.* 72000 €) and maxima in 2011 (with *ca.* 237000 €, 11% of the TR generated within the SCI). In 2009, the TR was also high for all sectors combined (exceeding 180000 €), but it only represented 6% of the TR generated within the SIC. This contrasts with the much higher TR detected outside the proposed sectors, specifically at both sides of the Guadalquivir Diapiric Ridge (Figs. 3 and 5). Considering all sectors combined, the deep-water rose shrimp generated the largest TR during the time series, contributing more than 120000 € in 2011, followed by the Norway lobster with *ca.* 60000 €. Nevertheless, the TR obtained by the Norway lobster exceeded those of the deep-water rose shrimp in 2007 and 2008 (Table 4).

Considering the proposed sectors separately, the largest TR was detected in Anastasya sector (in accordance to the high bottom trawling activity and catches), with an annual average of 77000 € during the time series (Table 4). Maximum TR values for this sector were detected in 2009 (120000 €) and minimum ones in 2007 (*ca.* 42000 €). Cristóbal Colón sector was the second one with the largest TR, with an annual average of more than 27000 € together with maxima in 2011 (*ca.* 43000 €) and minima in 2007 and 2008 (*ca.* 12000 €). In both sectors, the species that generated the highest TR were the deep-water rose shrimp and the Norway lobster (Table 4). Tarsis and Pipoca sector contributed with an average annual TR of around 24000 € during the time series, with minima in 2010 (*ca.* 1000 €) and maxima in 2011 (*ca.* 70000 €), following fluctuating catches during the time series (Table 1 and Table 4). Finally, Chica and Gazul sectors (with low to very low bottom trawling activity) generated the lowest average annual TR with 1000 and 5000 €, respectively, during the time series (Table 4).

Fig. 4B displays the annual total revenue (€) as a function per unit effort (hours) (TRUE) in the SCI and in all proposed sectors combined during the time series. The TRUE of all sectors combined represented values below 10%, with minima in 2007 (6% of the TRUE for the whole SCI) and maxima in 2009, 2011 and 2012, due to the high catches of the deep-water rose shrimp at Anastasya and Cristóbal Colón sectors (Table 4). Supplementary Fig. S2 displays the spatial distribution of the TRUE, as a function of bottom trawling activity (effort), along the time series. In general, the highest TRUE values were concentrated on both sides of the Guadalquivir Diapiric Ridge and in the westernmost part of Anastasya as well as Tarsis and Pipoca sectors.

3.4. Landed catches and total revenue of caught commercial species in relation to the fishing harbours

The fishing harbours with the largest total landed catches obtained in the SCI are located in the Huelva province, with those of Isla Cristina (IC), Ayamonte (AYA) and Punta Umbría (PU) being the most important ones (up to 91.2% of all catches from the SCI in 2007) (Fig. 6). During the time series, IC harbour displayed the largest average annual total landed catches from the SCI with *ca.* 80 t (maxima in 2009), followed by AYA harbour with *ca.* 50 t (with an increasing trend during the time series and a decline in 2012), and PU harbour with *ca.* 30 t (displaying a fluctuating annual trend) (Fig. 6A). The fishing harbours with the lowest annual total landed catches from the SCI were those of El Puerto de Santa María (PSM) (average of *ca.* 18 t), Sanlúcar de Barrameda (SBA) (*ca.* 11 t) and Huelva (HU) (*ca.* 9 t).

Considering all proposed sectors combined for a potential bottom trawling regulation, the fishing harbours that displayed the largest annual landed catches were also IC (average of *ca.* 9.38 t), AYA (*ca.* 6.10 t) and PU (*ca.* 1.95 t) (Fig. 6A). They displayed a similar temporal trend than that for the total annual landed catches from the SCI, except in PU that displayed similar values during the time series. The fishing harbours with the lowest annual total landed catches from all sectors combined were those of SBA and HU (in both cases *ca.* 0.4 t), followed by PSM (average of *ca.* 0.3 t).

Considering all the proposed sectors combined, the TR displayed a similar trend to that of the landed catches from those sectors, with IC (average annual TR of *ca.* 65000 €), AYA (*ca.* 45000 €) and PU (*ca.* 18000 €) harbours displaying the largest values (Fig. 6B). The harbours with the lowest TR were those of PSM, SBA and HU (in all cases *ca.* 4000 €). In general, the TR of those harbours from catches of the proposed sectors is less than 10% of their TR from the SCI. Considering this, IC, AYA and PU harbours could be the most affected ones in relation to a potential bottom trawling regulation in some sectors. Throughout the time series, a fluctuating increasing trend has been detected in the TR of IC and AYA from these sectors, but the remaining harbours displayed similar TR during the time series. A similar temporal trend was detected in the TR from the SCI regarding the different harbours, highlighting the sharp fluctuating increase in AYA harbour (Fig. 6B).

4. Discussion

This study shows the usefulness of the combined use of Vessel Monitoring System (VMS) data, logbook data and market prices of commercial species for analyzing the spatial and temporal evolution of the bottom trawling activity (effort), the associated catches and total revenue (TR) as tools for Marine Protected Areas management plans. Using this methodology it is possible to detect those areas with high cumulative impact on the seabed and others that generate high TR in the Site of Community Importance (SCI) of the "*Volcanes de fango del golfo de Cádiz*" (ESZZ12002). By comparing this information, it is possible to have a gross estimation of the economic impact of a bottom trawling regulation in some sectors in the future Special Area of Conservation (SAC). These sectors may respond to previous habitat protection proposals (Díaz-del-Río et al., 2014; Rueda et al., 2012a; b, 2016; Palomino et al., 2016; González-García et al., 2020a; b; Lozano et al., 2020b; Urra et al., 2020) and this should be discussed between the different parties implicated (government and fishermen) during the elaboration of the management plans of the SAC.

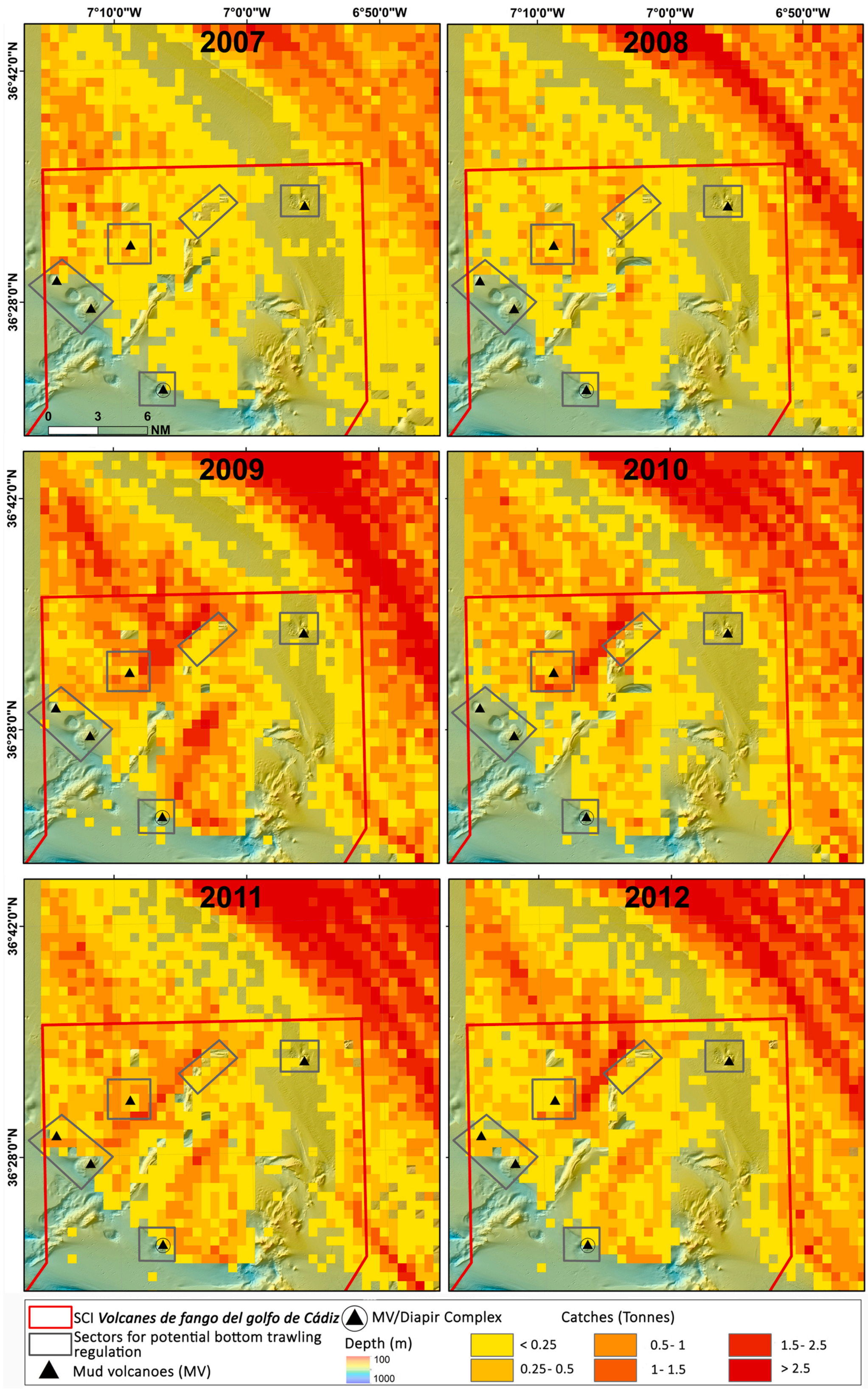

Fig. 3. Spatial distribution of the total annual catches (Tonnes) (based on VMS and logbooks data) of all commercial species per 1 km^2 grid cells in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*", including the different sectors proposed for potential bottom trawling regulation (Fig. 1 and Table S1), and the adjacent shelf and slope of the Spanish margin of the Gulf of Cádiz, during 2007–2012.

Table 4

Landed catches (Catches) (Tonnes, t) (based on VMS and logbook data) and estimation of total revenue (TR) (Euros, €) of the main commercial species caught in the different sectors proposed for potential bottom trawling regulation (Fig. 1 and Table S1) of the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" during 2007–2012. NEP: *Nephrops norvegicus*; DPS: *Parapenaeus longirostris*; HKE: *Merluccius merluccius*; MON: Monkfish group; OTR: Other fishes and crustaceans species (WHB: *Micromesistius poutassou*; RSH: Red shrimp group; OST: Osteichthyes group; PRA: Prawn group; CEP: Cephalopods group; ELA: Elasmobranchs group; OFI: Other fishes group; OCR: Other crustaceans group). Estimations of TR were done from VMS data, logbooks data and average market price of species provided in 2020 by the Andalusian Information System on Marketing and Fish Production Data of the "Dirección General de Pesca y Acuicultura de la Junta de Andalucía" (IDAPES) (Table S2 Suplementary material).

		2007		2008		2009		2010		2011		2012	
		Catches	TR	Catches	TR	Catches	TR	Catches	TR	Catches	TR	Catches	TR
Gazul	NEP	0.02	314.56	0.01	138.62	0.02	311.19	0.01	151	0.03	425.18		
	DPS	0.01	147.52	0.03	240.59	0.12	889.05	0.01	130.27	0.12	1001.05		
	HKE	0.01	59.50	0.01	43.11	0.02	70.10	0.01	28.82	0.01	47.47		
	MON	0.01	16.94			0.01	17.10			0.01	6.35		
	OTR	0.04	74.89	0.01	23.73	0.04	551.55	0.01	24.81	0.06	628.57		
Cristóbal Colón	NEP	0.23	3610.90	0.47	6711.08	0.57	8890.41	0.59	9152.55	0.84	12409.43	0.70	7879.60
	DPS	0.36	5296.29	0.44	3345.91	2.83	20263.96	1.09	11746.35	2.47	21018.34	1.75	16216.01
	HKE	0.10	497.25	0.08	355.89	0.19	603.09	0.45	1293.44	0.39	1354.86	0.27	936.89
	MON	0.07	471.82	0.04	163.32	0.04	268.34	0.06	307.36	0.10	576.88	0.06	324.93
	OTR	0.72	2376.74	0.45	1387.44	0.79	7962.88	3.19	6216.07	0.97	7432.31	0.88	3738.63
Anastasya	NEP	0.86	13422.49	1.41	20283.82	2.40	37302.33	1.97	30587.26	1.89	28039.98	1.24	14018.02
	DPS	0.99	14641.26	2.21	16819.13	8.68	62135.17	2.90	31307.88	7.08	60344.92	3.38	31361.75
	HKE	0.40	2015.07	0.76	3274.36	1.34	4331.63	1.53	4408.33	1.27	4364	0.93	3262.64
	MON	0.17	1076.66	0.19	1342.85	0.26	1790.89	0.25	1605.47	0.28	1712.68	0.12	518.11
	OTR	3.40	11121.09	3	7343.16	4.77	14743.80	7.98	18203.86	2.21	14725.61	1.91	5892.88
Tarsis/Pipoca	NEP	0.60	9430.40	0.37	5358.90	0.35	5509.91	0.02	343.16	1.07	15927.14	0.42	4759.45
	DPS	0.10	1414.66	0.16	1194.36	0.62	4430.88	0.02	237.36	4.02	34231.46	1.67	15461.87
	HKE	0.13	637.48	0.10	419.22	0.12	396	0.01	24.81	0.75	2573.59	0.37	1316.71
	MON	0.08	580.03	0.04	281.92	0.06	416.05			0.20	1453.75	0.04	217
	OTR	2.04	5581.13	0.55	1464.53	0.86	2540.55	0.10	144.94	1.86	16686.96	2.07	9212.71
Chica	NEP	0.08	1239.85	0.04	622.20	0.18	2742.10	0.06	978.36	0.18	2658.77	0.11	1288.15
	DPS	0.01	104.03	0.02	151.65	0.51	3637.40	0.08	887.25	0.44	3765.36	0.39	3655.23
	HKE	0.02	118.69	0.01	43.11	0.05	168.67	0.03	72.04	0.15	502.19	0.06	195.51
	MON	0.01	102.02			0.02	54.97			0.02	97.13	0.01	29.22
	OTR	0.10	628.10	0.09	171.04	0.14	671.93	0.13	294.50	0.50	5124.13	0.16	1069.59
SCI	NEP	20.91	326846.46	25.45	365869.63	43.60	677467.72	28.85	446960.47	32.80	486075.44	30.99	350541.92
	DPS	11.40	168098.44	41.65	316463.40	187.09	1340030.86	49.71	537565.93	128.55	1095457.62	101.13	938268.39
	HKE	7.40	37470.23	9.88	42607.85	21.36	69235.43	23.15	66709.45	23.47	80585.31	17.38	61236.44
	MON	4.46	27485.40	4.61	28572.25	4.56	26857.23	4.20	19731.16	5.82	28206	3.74	15838.93
	OTR	62.25	201763.89	49.98	160006.98	79.02	668959.90	100.79	263663.53	60.42	453759.56	51.36	198795.06

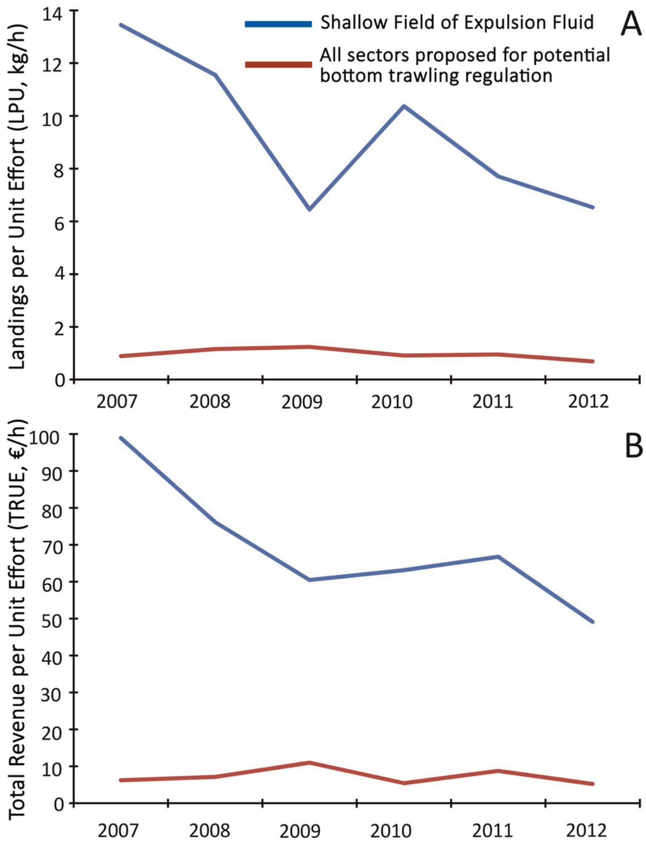

Fig. 4. A) Evolution, with estimated average values, of the landed catches (Tonnes, t) Per Unit of Effort (hours) (LPU) (based on the VMS and logbooks data); B) Total Revenue (Euros, €) per Unit of Effort (hours) (TRUE) in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" during 2007–2012. Data for of the SCI and for all of the proposed sectors for potential bottom trawling regulation (Fig. 1 and Table S1) are displayed.

During the time series (2007–2012), the spatial distribution of the bottom trawling activity (effort) within the SCI showed a similar pattern with some differences in relation to the depth and the target species. In this way, the largest bottom trawling activity was concentrated outside the SCI, mainly in shelf areas, with a decrease when approaching to the SCI. This would be explained by the multi-species trawling fishery of the north-eastern Gulf of Cádiz (GoC) and the presence of numerous fishing grounds of different species of high economic value, such as the European hake (*Merluccius merluccius*), caramote prawn (*Penaeus kerathurus* (Forskål, 1775)) or wedge sole (*Dicologlossa cuneata* (Moreau, 1181)), among others (Ramos et al., 1996; Jiménez et al., 1998), all of them mainly located on the shelf. In addition, due to a reduced vessel number with defined technical characteristics suitable for trawling on the continental slope (*e.g.* greater vessel length and power), most of the fishing fleet is concentrated in the continental shelf areas of the north-eastern GoC (Sobrino et al., 1994; Jiménez et al., 2004).

Bottom trawling activity was high around the Guadalquivir Diapiric Ridge (eastwards and westwards), as well as at Anastasya and Cristóbal Colón sectors. Environmental variables such as the bottom type (sedimentary *vs.* hard bottoms) or near-bottom current speed can significantly affect the distribution pattern of the bottom trawling activity because some target species may not occur in some bottom types or because bottom trawling operations can be difficult in those areas (González-García et al., 2020a). The main target species of the different fishing grounds located in the SCI include the Norway lobster (*Nephrops norvegicus*) and the deep-water rose shrimp (*Parapenaeus longirostris*) (Ramos et al., 1996). A high presence of muddy bottoms and low near-bottom current speeds (Medialdea et al., 2009; Sánchez-Leal et al., 2017; Lozano et al., 2020b) may benefit the establishment of those target species as they mainly occur in these environments (Abelló et al., 2002). Moreover, areas with high bottom trawling activity in the north-eastern GoC are characterized by the combination of those two environmental variables where bottom trawling operations are more effective (González-García et al., 2020a; b). The spatial trend of bottom trawling activity within the SCI showed high activity in the sedimentary areas at both sides of the Gusano Channel while low activity coincided with areas close to the channels and the diapiric ridges. Some sectors proposed for a potential bottom trawling regulation, where there is significant bottom trawling activity (*i.e.* Anastasya sector), coincide with environmental characteristics that are ideal for the trawling fleet to operate. Although there is a high level of bottom trawling activity, a high biodiversity of epibenthic and demersal fauna (*ca.* 300 taxa) has been detected in those areas (Delgado et al., 2013; González-García et al., 2020a; b) but some fragile and sensitive species to bottom trawling are extremely scarce there (*e.g. Isidella elongata*) (Díaz-del-Río et al., 2014; González-García et al., 2020b).

Anastasya sector, with an area of 21 Km^2, is included within a fishing ground known by fishermen as "*El Laberinto*" (the labyrinth in English), and the high bottom trawling activity could be linked to favourable conditions for the bottom-trawling operations and the abundance of some of the target species as commented previously. Despite the high bottom trawling activity, this small sector should have a bottom trawling regulation because it harbours singular and vulnerable chemosynthesis-based communities, including bacterial mats, frenulated polychaetes and endemic chemosymbiotic bivalves of mud volcanoes (MV) of the GoC (*i.e. Solemya elarraichensis*, *Lucinoma asapheus*) (Habitat 1180 of the Habitat Directive, Submarine structures made by leaking gases) as well as sea-pens and burrowing megafauna communities, included in the OSPAR list of Threatened Habitats (Rueda et al., 2012a, 2016). Palomino et al. (2016) indicated that these GoC endemic chemosymbiotic species and mud breccia sediments were more abundant at the summit of Anastasya MV (central part of the proposed sector) than on its adjacent bottoms. This may partly explain the lower fishing activity in the central part of this sector because the summit of Anastasya MV contains high ammounts of sticky mud (coming from the mud breccia expulsed together with the fluids) (Palomino et al., 2016). Moreover, this area is also known by local fishermen as an area with a high probability of muddying which can cause the brokedown of the net. Nevertheless, the intense bottom trawling in this sector (mainly in 2010–2012) may cause changes in sedimentary characteristics and direct physical damage to the seabed (Jennings and Kaiser, 1998; Kaiser et al., 2003; Pauly, 2003). This may produce impacts such as burial of the bacterial mats and removal of the infaunal chemosymbiotic invertebrates occurring at the summit of this MV (Rueda et al., 2012a, 2016; González-García et al., 2020b). Although some communities of cold seep habitats may be more vulnerable than the typical communities of the adjacent sedimentary habitats, the effects of trawling over them have been rarely evaluated (Ramírez-Llodra et al., 2011). It is expected that a new regulation of the bottom trawling activity in the sector may not result in a high economic impact (based on the TR estimations) but the medium/long time benefits could result in an increase of the mobile commercial species abundance to adjacent fishing grounds. Although there are no previous studies on the effects of bottom trawling regulation in certain areas of the north-eastern GoC, similar studies in different parts of the world have shown an increase in the abundance of different commercial species in areas located close to no-take areas within 2–5 years due to an export of adult biomass (spillover effect) and/or larvae (recruitment effect) (Roberts et al., 2001; Gell and Roberts, 2003; Pierpaolo et al., 2013). According to a study by Palumbi (2004), the spillover effects from a marine protected area could cover up to 100 km while larval dispersal from 50 to 200 km for fish and from 10 to 100 km for invertebrates. Thus, a potential bottom trawling regulation of this sector, together with the others proposed, could favour the restoration of populations of highly stressed species and, in the mid-long term, benefit

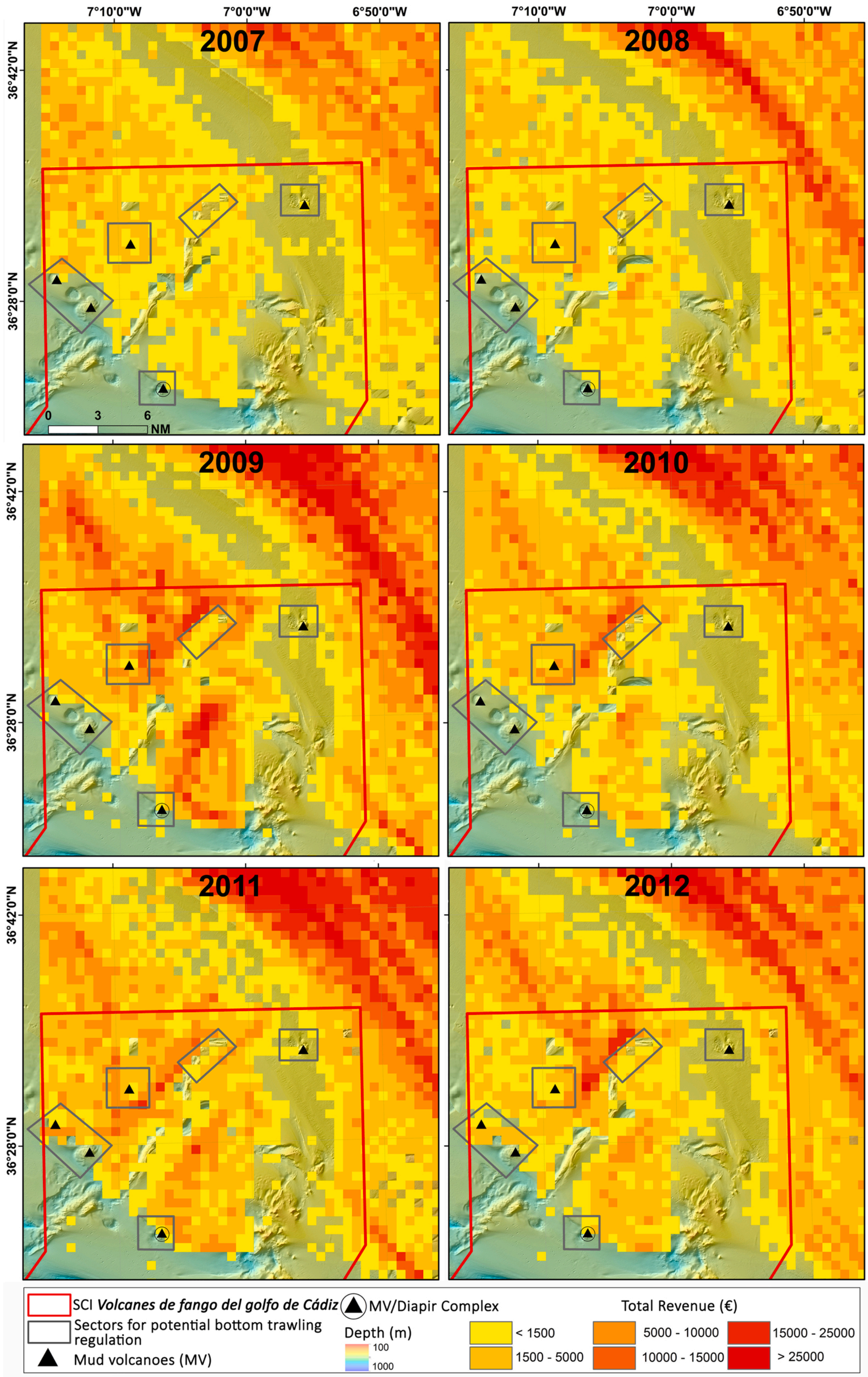

Fig. 5. Spatial distribution of the annual total revenue (Euros, €) associated with catches of all commercial species from Table 2 expressed in Euros per 1 km^2 grid cells in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*", in sectors proposed for potential bottom trawling regulation (Fig. 1 and Table S1) and in the adjacent shelf and slope of the Spanish margin of the Gulf of Cádiz, during 2007–2012.

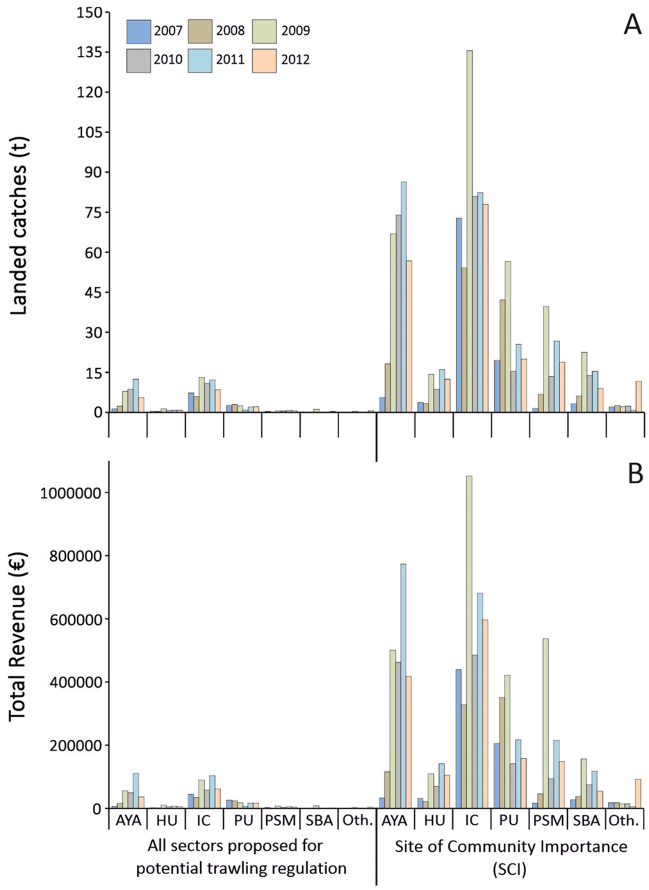

Fig. 6. A) Evolution, during the time series, of landed catches (in the main fishing harbours) of commercial species (Tonnes, t) in the Site of Community Importance (SCI) "*Volcanes de fango del golfo de Cádiz*" and in all the different sectors proposed for the potential bottom trawling regulation; B) Evolution of the estimation of the associated with landings total revenue (TR) (Euros, €) (in the main fishing harbours) from the SCI and in all the different sectors proposed for the potential bottom trawling regulation. AYA: Ayamonte; HU: Huelva; IC: Isla Cristina; PU: Punta Umbría; PSM: El Puerto de Santa María; SBA: Sanlúcar de Barrameda. Estimations of TR were obtained by combining VMS and log-books data with average market price of species (IDAPES).

the bottom trawling fleet operating in adjacent areas.

A low bottom trawling activity was detected in Gazul (14.8 Km^2) and Chica (14.9 Km^2) sectors and low-medium activity in Tarsis and Pipoca sector (37.7 Km^2) as well as in areas close to channels or diapiric ridges. Moreover, catches and associated TR were also low in those areas. This could be explained by unfavorable conditions for bottom trawling and the absence of some target species as commented previously. Generally, in these sectors a moderate-high near-bottom current speed occurs which causes seabed erosion and the exhumation of different hard substrates (*e.g.* methane-derived authigenic substrates, bioclasts) that are not ideal for some target species and bottom trawling operations (Palomino et al., 2016; Sánchez-Leal et al., 2017; González-García et al., 2020b; Urra et al., 2020). This would confirm the results of recent studies in the SCI in which these environmental variables play an important role in the distribution of different habitats and associated species, including those with high commercial interest such as the Norway lobster or the deep-water rose shrimp (González-García et al., 2015, 2020a; b; Lozano et al., 2020a). This combination of an adecuate hydrodynamic environment with hard and mixed substrates and low anthropogenic impact benefit some key deep-sea habitat-forming species with slow growth such as colonial scleractinians, gorgonians and deep-sea sponges (Hiddink et al., 2007; González-Irusta et al., 2018; Urra et al., 2020). Indeed, a high diversity of benthic habitats included as Habitat 1170 (Reefs) of the Habitat Directive have been detected in these sectors such as *Madrepora oculata-Lophelia pertusa* reefs, deep-sea sponge aggregations, bamboo coral communities and gorgonian aggregations (Rueda et al., 2012a, 2016; Díaz-del-Río et al., 2014; Palomino et al., 2016; Sitjà et al., 2018; González-García et al., 2020b; Urra et al., 2020) (Table S1). Some of those studies indicated that those areas are biodiversity hotspots for the north-eastern GoC and they still represent pristine or little exploited areas by fishermen. In addition, Tarsis and Pipoca sector contains chemosynthesis-based communities (included in the Habitat 1180 - Submarine structures made by leaking gases of the Habitat Directive), mostly at the summit of Pipoca MV, whereas these communities are less dense and diverse at the summit of Tarsis MV (Rueda et al., 2012b; Palomino et al., 2016). A bottom trawling regulation in this sector may not produce a large impact on the TR of the fishermen, and may delimitate these areas that can represent a danger for bottom trawling operations due to entanglement of the nets and gears, which generally are highly priced.

High bottom trawling activity has been detected in the SCI during the first three years of the time series, with a reduction in 2010 and an increase in the following two years. The factors that may influence temporal changes of the bottom trawling activity may have different origins and may induce some spatial and/or temporal changes in the bottom trawling activity. Influencing factors can be the weather and sea conditions, the biological productivity (spatial distribution of commercial species), the season when fishing takes place (biological closures in autumn) or the distance of the fishing grounds to the fishing harbours (Abesamis et al., 2006; Stelzenmüller et al., 2008). Prieto et al. (2009) showed how the combination of the seasonal cycle and meteorology (wind regime and high rainfall events) can promote high annual productivity in a short time in the GoC continental shelf. On the other hand, González-Ortegón et al. (2015) suggested that water scarcity in the Guadalquivir estuary causes periods of extremely high and persistent turbidity with a consequent reduction of the biological productivity in some shelf areas of the GoC. This latter study showed that 2008 and 2009 (years with low to moderate rainfall), resulted in a period of high turbidity which could have influenced an increase in the fishing effort within the SCI due to a decrease in the abundance of target species in the continental shelf area. On the other hand, some social and/or economic factors could also induce changes in the bottom trawling activity such as local fishermen's traditions, the increase in fuel prices or the stagnation of market prices for target species (Stelzenmüller et al., 2008; Abernethy et al., 2010; Cheilari et al., 2013). During this period, as in other regions of the world, there was an upward fluctuation in fuel prices (https://www.huelvainformacion.es/provincia/gasto-barco-gasoil-euros-semana_0_154184726.html), representing one of the significant costs of the bottom trawling fleet, and therefore of their profitability (Abernethy et al., 2010; Cheilari et al., 2013). The exploitation of decapods (the Norway lobster and the deep-water shrimp) is in general more profitable in terms of market prices when compared to other commercial species in the GoC (Table S2, supplementary material). Moreover, throughout the time series, the prices for these two species decreased (average price of the Norway lobster in 2007 was 15.63 Euros/kg to 11.31 €/kg in 2012 and from 14.75 €/kg in 2007–9.28 €/kg in 2012 for the deep-water rose shrimp) (Table S2, supplementary material). In addition, the fuel consumed for catching these species can triple their consumption compared to bottom trawling targeting other species (Thrane, 2008; Abernethy et al., 2010). The combination of these two factors could imply an increase in bottom trawling activity in fishing grounds, mainly those close to harbours, as observed in other parts of the world (Cheilari et al., 2013) to compensate for the costs. This could explain the increase in bottom trawling activity within the SCI in 2009, both fishing hours and trawling vessels (Table 1) with the result that the landed catches as total revenue per unit effort (LPU, TRUE) (Fig. 4) decreased for the SCI. On the contrary, a slight increase in LPU and TRUE was observed in all sectors proposed for potential bottom trawling regulation and this could be related to lower bottom trawling activity in previous years which could have led to a slow recovery of the different species as well as the high catch rate of the deep-water rose shrimp observed that year (Table 3).

An increase in bottom trawling activity and a decrease in LPU has been detected in the SCI for 3 consecutive years (Fig. 2 and Fig. S1), which could indicate that some target commercial species are suffering from a high degree of exploitation and, therefore, a decrease in catches, as it has been detected in other areas of the world (Christensen et al., 2003; Myers and Worm, 2003). Torres et al. (2013) already indicated that the north-eastern GoC was in a high stress and displaying signs of a highly exploited ecosystem. This is in accordance with other studies for the European margin in which the bottom trawling impact is exerting a negative pressure on different ecosystemic components comparable to that detected in highly exploited ecosystems (Sánchez and Olaso, 2004; Coll et al., 2007, 2010). This could explain the increase in bottom trawling activity to deeper areas (Chica as well as Tarsis and Pipoca sectors) in the last years of the time series confirming the idea of a possible progressive depletion of the trawling fleet target fishery resources, as it has been observed in other areas of ICES region IXa (Bueno-Pardo et al., 2017; Ramalho et al., 2017) and in other regions of the world (Baum et al., 2003; Christensen et al., 2003; Myers and Worm, 2003). This is in accordance to other studies where expansion into new fishing areas fare away from the coast, is seriously threatening some deep-sea species and habitats (Morato et al., 2006; Watson and Morato, 2013).

The largest catches of both the deep-water rose shrimp and the Norway lobster matched the different fishing grounds of these species in the north-eastern GoC (Ramos et al., 1996). Nevertheless, temporal changes in the catches of these crustaceans were detected during the analyzed time series. Considering that these species are highly exploited in the study area, differences in the catches could be partly a response to their particular life cycle as observed in previous studies in other areas of Europe (Abelló et al., 2002; Sbrana et al., 2003). The deep-water rose shrimp is a short-living species with a high growth and mortality rate (Abelló et al., 2002) and its abundance may be conditioned by annual recruitments which could explain the large inter-annual fluctuations in the north-eastern GoC (Sobrino and García, 1998). In contrast, the Norway lobster is a species with a long life cycle (Abelló et al., 2002) and is subject to specific fishing plans for the bottom trawling fleet making its catches dependent on the various quotas that are published annually. In 2009 and 2011, there was an increase in catches of the deep-water rose shrimp (higher abundance), so the bottom trawling activity directed to this species increased and, consequently, catches of the Norway lobster also increased as they occur in similar environments. This, together with the factors mentioned above (price of species and costs derived from fuel consumition), could explain the increased in trawling activity in different areas of the SCI and therefore in the sectors proposed for a potential bottom trawling regulation (mainly Anastasya).

The harbours with the largest landed catches and TR coming from the different sectors proposed for a potential bottom trawling regulation were Isla Cristina (IC), Ayamonte (AYA) and Punta Umbría (PU) (Fig. 6A and 6B). Nevertheless, the values represented a small percentage (*ca.* 10%) of those from the whole SCI, so in general, a little impact on the incomes generated by the fishermen is expected after new bottom trawling regulation of those sectors. Nevertheless, it is unknown how this could affect other economic activities (*e.g.* restaurants, fish markets) that depend on the catches by fishermen. This impact could be balanced by a proportional increase of subsidies to fishermen and by promoting a transition to other fisheries modalities that may cause less damage to the seafloor. In general, the number of vessels coming from different harbours, the proximity of the fishing grounds being exploited, the fishing gear used by the vessel, the fuel costs in different harbours, the market prices in different localities, can directly influence the amount of landed catches in a given harbour because a high market value of the product can balance the fishing costs and that fishermen need to take into account in order to benefit from fishing activities (Stelzenmüller et al., 2008; Bastardie et al., 2010b; Basurko et al., 2013). Landings of catches, independently of the vessel's harbour of origin, are done in one harbour or another based on the commercial value and demand of the product in specific harbours, and this can partially balance the costs arising from the activity (Stelzenmüller et al., 2008; Junta de Andalucía, 2011; Bueno-Pardo et al., 2017). For example, the average price of the deep-water rose shrimp in AYA harbour is usually 33.5% higher than in IC harbour (Junta de Andalucía, 2011), because larger specimens are preferred in AYA. In this case, social and/or economic factors that may affect landings in a given fishing harbour must be taken into account so the potential bottom trawling regulation of these sectors may not have a negative impact in one specific harbour. The strategy involving searching for the best harbours to land the daily catches in order to lower costs has also been observed in harbours of southern Portugal, with no direct correlation between the fishing effort assigned to a harbour and the catch landed tonnes in the same harbour (Bueno-Pardo et al., 2017).

This study could only provide estimations of the total revenue (as a proxy of the economic profit), but it would be interesting to carry out a more detailed study for estimating a reliable economic profit obtained from the interaction of the total income of the species caught (some more profitable than others) (generally known as total revenue) with the economic costs (losses) associated with the bottom trawling activity (Sethi, 2010). For estimations of the costs associated with the bottom trawling operations, it would be necessary to take into account different aspects that are difficult to obtain and quantify, such as (1) the variability of prices between the different fishing harbours in the area and the temporal fluctuations in fuel prices; (2) the fuel consumption of the different vessels and during different weather conditions (*e.g.* fuel consumption may be higher in stormy weather conditions); (3) the number of employees and their monthly salaries on the different vessels and different times of the years; (4) the associated annual cost of vessel maintenance (breakage or loss of fishing gear, damage to equipment, *etc.*); (5) the harbour and other taxes, among others. The lack of information on these aspects make it difficult to carry out a more exhaustive study of the final economic profits obtained by the bottom trawling fleet operating in the study area and in the sectors for potential bottom trawling regulation. Reliable data on costs associated with the bottom trawling operations is a common state for fisheries around the globe. In general, fisheries regulators in many countries dedicate considerable resources for studying the biology and ecology of regulated species, but little resources are generally invested for properly understanding the economic and social dynamics of commercial fisheries. This requires an investment in data collection programs from governments and organizations that could enhance the knowledge of average and marginal costs associated with the bottom trawling operations. This will provide a unique opportunity for obtaing reliable estimates of economic profit that will be very useful in the rule-making process, and for the management plans of the future SAC "*Volcanes de fango del golfo de Cádiz*".

The bottom trawling activity and the catches of target species (the Norway lobster and the deep-water rose shrimp) within the SCI "*Volcanes de fango del golfo de Cádiz*", during a relatively long period, are mainly concentrated in flat sedimentary areas around the Guadalquivir Diapiric Ridge, but at a much lower scale than in shallower areas outside the SCI. In the SCI, bottom trawling activity is increased in the last years of the time series, due to a possible depletion of fishery resources. The landed catches and TR in the different harbours appear to be influenced by economic and/or social factors based on the market price of the landed target species in those harbours and the costs associated (mainly related to fuel prices). A biological closure or a specific bottom trawling regulation should be implemented in the different sectors harbouring vulnerable and threatened habitats and species that are included in the Habitats Directive and other lists of threatened species and habitats (Fig. 1, Table S1; Díaz-del-Río et al., 2014; Rueda et al., 2012a; 2012b, 2016; Palomino et al., 2016; González-García et al., 2020a; b; Lozano et al., 2020b; Urra et al., 2020) as it has been done in other Natura 2000 sites. These sectors (Gazul, Cristóbal Colón, Anastasya, Tarsis and Pipoca, as well as Chica) occupy a small area of the Shallow Field of Fluid Expulsion (SFFE) of this SCI (106 km^2 and *ca.* 11% of the total area of the SFFE). The socioeconomic impact (landed catches and TR), following the new bottom trawling regulations in these sectors would not be high for the bottom trawling fleet and, in the long term, it could benefit from the spillover of commercial species living in these closed sectors to adjacent areas. Therefore, the potential bottom trawling regulation of these five sectors would be a sustainable management measure without serious socio-economic consequences which, with government support and/or awareness on the part of skippers towards the conservation of these habitats, could promote their restoration and the recovery of the various heavily exploited fisheries resources in the SCI. Moreover, through the conservation and protectection of habitats with a bottom trawling regulation of these sectors in the future SAC, progress would be made in the development of the different objectives established by the Marine Strategy Framework Directive (MSFD) (Council Directive, /56/EEC, 2008) and the Habitats Directive (92/43/EEC).

Fishing and harvesting of marine resources have been identified as one of the most common "high pressure" activites on habitats and species in marine Natura 2000 sites as it has been detected in the SCI "*Volcanes de fango del golfo de Cádiz*" (Díaz del Río et al., 2014; European Commission, 2018; Fraschetti et al., 2018; González-García et al., 2020a). Such activities are subject to Article 6 of the Habitats Directive, which sets out the provisions that govern the conservation and management of Natura 2000 sites (European Commission, 2018). In particular, Article 6(1) and 6(2) indicate the need for the establishment of the necessary conservation measures and the avoidance of habitat deterioration and significant species disturbance (European Commission, 2018). According to these articles and the results of the present study, it is of common sense that bottom trawling regulation should be implemented in some sectors of the SCI harboring threatened and vulnerable habitats. Fisheries management measures implemented at local, national and European Union levels in Natura 2000 sites have generally included: (1) Temporal and spatial limitations of fishing; (2) designation of fishing free zones; (3) prohibitions of fishing in certain habitats or with certain fishing gears; (4) testing and improvements of fishing gears for increasing the catchability of target species and for reducing the by-catch; (5) monitoring of the composition, abundance/biomass, size classes, damage and survival of the by-catch and (6) promoting education on protected features and fishermen's cooperation in conservating key habitats and species of the SCI (European Commission, 2018). As commented previously, bottom trawling produce significant negative effects on the seabed (*e.g.* Removal of non-target species, damage of fragile organisms -including habitat-forming species- and disturbance to substrate and habitat structure, turbidity, among others) and it is expected that is causing similar effects on the seabed of the SCI and this should be evaluated in future studies. In accordance of the results of the present study, it would be of importance to conduct participatory workshops with the different stakeholders of this SCI in order to make proposals for the management plans of the SCI and to suggest some technical measures regarding how, where, and when fishermen may fish. Some Natura 2000 sites of Spain generally have implemented (1) a no-take zone where no extractive activities are permitted (*e.g.* integral reserve zone of Isla de Tabarca Marine reserve) (Purroy et al., 2014); (2) zones where some fishing modalities are prohibited (*e.g.* trawling, purse seining and competitive fishing in Cap de Creus National Park); (3) zones where regulated commercial and recreational fishing is allowed under a scheme of permits or licenses (*e.g.* Medes island) (Martín et al., 2012) and (4) a general use zone where all forms of fishing are permitted. A similar spatial approach could be developed in the studied SCI in order to improve management and sustainability of the bottom trawling regarding threatened habitats and species. Recently, regulations of bottom trawling effort and catch management typically include regulations on the number and types of boats/licenses, types of gear, number of trips and fishing hours as well as on the annual catch limits and quotas, which may also be helpful for reducing the seabed impact of bottom trawling in specific sectors or periods of time as performed in some Natura 2000 sites (ICES, 2011; European Commission, 2018). In the north-eastern GoC (including the SCI), there are some compulsory bottom trawling regulations and different management measures such as (1) the bottom trawling effort cannot exceed 200 days per year and/or 18 h per day; (2) vessels can trawl during a maximum of 5 days per week and must rest for at least 56 continuous hours; (3) mesh dimensions of the bottom nets must be equal to or greater than 55 mm; (4) a temporary closure of *ca.* 90 days (September to November); (5) monitoring and evaluation programs of fisheries stocks (*e.g.* ISUNEPCA, ARSA expeditions) and (6) the establishments of quotas for some commercial species (*e.g.* Norway lobster) (BOE, 2009). All these management measures are highly needed for reducing the bottom trawling impact on commercial species that are overexploited (*e.g.* hake, Norway lobster). Nevertheless, these management measures are insufficient for some habitats that are highly sensitive to bottom trawling in the GoC and new measures should be implemented in accordance to achieve a Good Environmental Status under the framework of the MSFD. A combination of different management measures could be implemented in the SCI after discussion with the different stakeholders, together with other measures that are more difficult to implement such as multipurpose habitat management, as well as quotas on invertebrate by-catch or habitat-impact based on monitoring and evaluation of benthic habitats of the SCI (McConnaughey et al., 2020). The present study may represent a contribution to management plans of the future SAC, which may also benefit from the active participation of different stakeholders (*e.g.* government representatives, fishermen, scientists) and further research on the specific impacts of bottom trawling in habitats and species in the fishing grounds of the north-eastern GoC as basic tools for decision making.

CRediT authorship contribution statement

E. González-García: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Á. Mateo-Ramírez:** Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **M.P. Maroto Castaño:** Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **G. Bruque:** Formal Analysis, Data curation, Writing – review & editing. **C. Farias:** Formal analysis, Writing – review & editing. **N. López-González:** Formal Analysis, Investigation, Writing – review & editing. **A. Punzón:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Visualization. **J.L. Rueda:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106420.

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