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New technologies can support data collection on endangered shark species in the Mediterranean Sea

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ABSTRACT: In the last 50 yr, shark populations showed steep declines in the Mediterranean Sea. The IUCN lists most Mediterranean species as threatened (55%), while considering 27.5% of them Data Deficient. Here, sharks are currently one of the rarest and more elusive groups of animals, and data from fisheries and scientific monitoring still insufficiently support robust abundance and distribution assessments. New technologies can fill this data gap by linking people and scientists through new monitoring strategies. SharkPulse, an international collaborative project, aims at creating a large world database of shark occurrence records by mining images on the web, social networks, and private archives. Here we analyzed 1186 sharkPulse records from the Mediterranean Sea. We collected records to characterize spatio-temporal patterns on 37 species, highlighting distribution changes for 5, and, by using generalized linear models, estimating trends in sighting for the most abundant species. With 273 records, *Hexanchus griseus* had the most sighting records since the beginning of the series. We identified pupping areas and aggregation sites for immature *Prionace glauca* and *Isurus oxyrinchus*; pinpointed strongholds of the Critically Endangered *Squatina squatina* to focus conservation efforts; and identified broader than previously reported regional distribution ranges for *Alopias superciliosus*, *Dalatias licha*, *Heptranchias perlo*, *H. griseus*, *Oxynotus centrina*, and *P. glauca*. We confirmed that fishing is still the major threat for Mediterranean sharks and call for a greater effort in controlling the emerging patterns with efficient conservation effort indexes. If properly standardized, opportunistic data can efficiently and cost-effectively advance our understanding of shark abundance, distribution, and conservation status.

KEY WORDS: Citizen science · Data mining · Elasmobranchs · Opportunistic data · Abundance · Distribution

1. INTRODUCTION

The conservation status of sharks in the Mediterranean Sea is one of the worst on the planet (Dulvy et al. 2014, Cashion et al. 2019, Bargnesi et al. 2020b, Walls & Dulvy 2020, 2021, Milazzo et al. 2021). The International Union for the Conservation of Nature (IUCN), has assessed 40 shark species in the area (Dulvy et al. 2016, Walls & Dulvy 2020). Among them, 22 species (55%) are listed as threatened and 11 (27.5%) still do not have enough data to assess their status (i.e. listed as Data Deficient). This makes the Mediterranean Sea one of the areas with the world's highest percentage of threatened shark spe-

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cies (Walls & Dulvy 2020). Pelagic shark populations showed declines up to 98–99% over the last 50–200 yr (Ferretti et al. 2008, Moro et al. 2020), and there is a long list of coastal and demersal species that are on the edge of local extinction, such as the angelsharks (*Squatina* spp.) (Fortibuoni et al. 2016) and the sand tiger shark *Carcharias taurus* (Bargnesi et al. 2020a), or have even already been extirpated from the area (Ferretti et al. 2016, Lawson et al. 2020).

Detecting the occurrence and distribution of species is an important first step to defining efficient conservation plans. They can identify critical habitats and ongoing threats (Gordon et al. 2019). Range contraction and area of occupancy fragmentation can identify population declines (Mace et al. 2008, Worm & Tittensor 2011, Moro et al. 2020). Yet locations where species are still present can indicate conservation opportunities and important habitats acting as strongholds from which endangered species could be preserved and potentially recovered.

In the Mediterranean Sea, the poor conservation status of sharks (Dulvy et al. 2016, Walls & Dulvy 2020, 2021) is mainly driven by overfishing (Dulvy et al. 2014, 2016). Most of the sharks' fishing mortality is in the form of by-catch, occurring in several fisheries such as longline, small scale, and bottom trawl fisheries (Cavanagh & Gibson 2007, Bradai et al. 2018, Serena 2021). Sharks were historically targeted by many coastal fisheries, especially off-season (Ferretti et al. 2008, 2013, Fortibuoni et al. 2010), and some species are still marketed, such as smoothhounds (*Mustelus* spp.), catsharks (*Scyliorhinus* spp.), and dogfishes (*Squalus* spp.). Libya, Tunisia, Italy, Spain, Greece, and Turkey are major shark fishing countries in the Mediterranean Sea (Cavanagh & Gibson 2007, Bradai et al. 2018). Sharks are also caught in recreational fisheries (Ferretti et al. 2008), which have been shown to substantially impact marine resources and ecosystems in the area (Font & Lloret 2014, Lloret et al. 2020, Panayiotou et al. 2020), though the full impact of these fisheries on sharks has yet to be shown (GFCM 2021).

Shark fisheries statistics in the Mediterranean Sea are often inadequate for stock assessment because of unreported catches, low taxonomic resolution, and poor monitoring of fishing activities (Cashion et al. 2019). This condition has also impaired research on the biology and ecology of many species, even for broad-ranging and widely distributed species such as large pelagic sharks. Life histories, population structure, abundance, and spatial ecology of many of these species are still hypothesized in the Mediterranean Sea (Damalas & Megalofonou 2012, Moro et al. 2020), as is the role of this region for their ecology. For example, it has been proposed that the Mediterranean Sea may host important nursery areas for pelagic sharks (Costantini & Affronte 2003, Soldo 2005, Megalofonou et al. 2009, Jambura et al. 2021). Newborns, juveniles and immatures, and pregnant females of great white sharks *Carcharodon carcharias* (Saidi et al. 2005, Kabasakal & Gedikoğlu 2008, Kabasakal 2020, Leone et al. 2020, Scannella et al. 2020), blue sharks *Prionace glauca* (Megalofonou et al. 2009, Giovos et al. 2020), and shortfin makos *Isurus oxyrinchus* (Kabasakal 2015a, Udovičić et al. 2018, Giovos et al. 2020) have been repeatedly observed in multiple sectors of the Mediterranean Sea. However, no study has yet tested, under well-defined criteria (Heupel et al. 2007), whether these occurrences indicate the presence of nursery areas.

Boosting data collection on the presence of Mediterranean sharks is crucial to increasing our understanding of these populations and promoting new and more efficient conservation strategies in the region. Despite its chronic lack of scientific data, the Mediterranean Sea offers a tremendous opportunity to deepen our knowledge of sharks with the use of unconventional data sources. This is one of the most densely populated regions in the world, with heavy ocean use and tourism (EEA 2015, Tovar-Sánchez et al. 2019, Moro et al. 2020). Citizen science is increasingly used as a tool of ecological investigation and data collection (Bonney et al. 2009), and new technologies can boost these activities by linking scientists with many people increasing the scale and resolution of data collection (Kobori et al. 2016). Web platforms and mobile applications have already given good results in terms of quantity and quality of data collected (Sullivan et al. 2014). This is also true in the Mediterranean Sea, where programs targeted to the collection of shark sightings already exist (Bargnesi et al. 2020b). However, most of these are still limited to specific species and/or restricted to specific regions such as the national waters of Greece, France, Malta, Israel, Libya, Italy, and Albania (Bargnesi et al. 2020b). These initiatives have gathered important information on threatened species such as the angelsharks (Giovos et al. 2019), basking sharks *Cetorhinus maximus* (Mancusi et al. 2005), and great white sharks (Moro et al. 2020). They have shown great potential to advance shark conservation in the region, but would greatly benefit from an increase in spatial scope (i.e. having a Mediterranean scale), coordination, and integration. In this way, all of the data streams could be merged into an open and flexible system of data collection, management, organization, and dissemination (Bargnesi et al. 2020b).

Here we propose to address this lack of regional monitoring, data integration, and standardized data collection by using sharkPulse. This crowdsourcing platform aims at building a global database of shark image-based sightings. Using different approaches to obtain, organize, and transform shark photographs into occurrence records, this international collaborative project has been warehousing shark images since 2014, globally (http:\\sharkpulse.org). We analyzed the Mediterranean portion of this database to show how harmonizing monitoring efforts based on sighting data can advance our understanding of the ecology and biology of sharks and improve their conservation status. We highlight the data's potential for addressing conservational issues in the area, including responding to data calls from the IUCN on distribution, trends, and threats affecting sharks in the Mediterranean Sea, especially for pelagic species (Ellis et al. 2016, Sims et al. 2016, Walls & Soldo 2016b). We also highlight the need for proper standardization, which, through a clear statement of assumptions, can generate biological and ecological indices useful to characterize geographical ranges, temporal patterns in abundance and distribution, population structures, and how these aspects are impacted by exploitation and other human stressors.

2. MATERIALS AND METHODS

2.1. Data collection

Data for this study were extracted from the sharkPulse database. We extracted all shark sightings recorded in the Mediterranean Sea, from the most historical sighting available (August 10, 1946) to April 2020. Valid sharkPulse records have at least the date and location of the photo. Species identifications are checked and validated by elasmobranch researchers, members of the sharkPulse team, using FAO field and taxonomic identification guides, and other specific regional guides (Bouchot 1987, Serena 2005, Otero et al. 2019, Ebert & Dando 2020, Serena et al. 2020). The database sources data with different approaches, from crowdsourcing ocean users to web scraping and mining social networks. Ocean users (e.g. scuba divers, fishermen, surfers) can submit shark pictures through both a dedicated web page (http:\\sharkpulse.org) and a mobile app (iOS and Android). Participation is actively stimulated by a systematic effort of social media outreach, i.e. new sightings are shared on the project's social network pages (Facebook, Twitter, Instagram). In addition, to reach an increasing number of ocean users, even beyond English-speaking groups, national focal points were created through dedicated Facebook pages in local languages. As of April 2022, the sharkPulse Italia Facebook page (facebook.com/SharkpulseItalia/) had >1000 followers and its posts usually reached between 200 and 2500 profiles. The Greek national focal point, sharkPulse Greece, was created in 2018 and provided 154 sightings from the Aegean Sea and the Eastern Mediterranean Sea. As for web and social network scraping, Phyton and R scripts were used to automatically extract and aggregate images identified or flagged as sharks from some web platforms (e.g. iNaturalist and Flickr) using the social networks' available application programming interfaces.

2.2. Data storage and analysis

SharkPulse data are stored in a PostgreSQL relational database (version 9.5.19). A valid sharkPulse record must contain data such as date, latitude, longitude, image name, and source (i.e. whether a submission is from a user through mobile or web platforms or the records are extracted from online portals or social networks). Additional information such as time, email, or contact of the source, device type, common name, and notes are optional. Images are stored in a dedicated server and linked to their metadata.

For this analysis, we identified the observation type, dividing our records into fishing observations (indicating where possible if the record came from a professional or recreational fishing event, or was recorded from a local fish market), diving observations, stranded specimens, and surface observation of a free-swimming animal (i.e. while on a boat or from the shore). In some cases, picture details allowed us to estimate shark size (e.g. total, fork, or standard lengths) by comparing the specimen with reference objects like a boat of known size or people handling the animal, and thus to determine whether the individual in the photograph was immature (i.e. by comparing the estimated size with published length at maturity). Dividing the depicted specimens into maturity stages was systematically done for 2 species: shortfin mako and blue shark. For the shortfin mako, we considered all specimens with an inferred total length (TL) <200 cm to be immature (Kabasakal 2015a). Similarly, a 120 cm TL threshold was set for immature blue sharks. Blue sharks estimated to be <70 cm TL were classified as newborn, or young-of-the-year (YOY), following Megalofonou et al. (2009).

Data analysis, mapping, and plotting were performed with R (R Studio, version 3.6.1). To each record, we associated the latest species-specific IUCN conservation status for the Mediterranean Sea (Dulvy et al. 2016). Furthermore, we downloaded the shapefiles of the species' geographical ranges from the IUCN Red List website (iucnredlist.org) and compared them with the distribution of our records. To underline other types of spatial information that opportunistic records can provide, we focused on the angelshark *Squatina squatina*, a Critically Endangered demersal species once widely distributed throughout the Mediterranean Sea (Fortibuoni et al. 2016, Lawson et al. 2020). We wanted to map areas where this species is likely still present and to relate those areas with the overall Mediterranean fishing effort. Mediterranean fishing effort was retrieved from the Global Fishing Watch database (Kroodsma et al. 2018). Presence areas were built assuming a 50 km buffer around each sighting location, since angelsharks have been observed not to travel large distances and have limited home ranges (Standora & Nelson 1977), although some seasonal movements have been hypostasized to occur in the family Squatinidae (OSPAR Commission 2010, Ellis et al. 2021, Noviello et al. 2021). We overlapped the buffers with bathymetric data provided by NOAA (Amante & Eakins 2009) and clipped the area encompassed between 5 and 150 m depth, which represents the bathymetric range of the species (Morey et al. 2019).

We also estimated temporal trends of abundance indices from these opportunistic datasets, limiting the analysis to the period 2014 to present, which is when the sharkPulse initiative has been active. The last 2 yr were excluded, as we expected a different observation effort regime due to COVID-19 pandemic-related biases. In this analysis, we estimated trends of the 5 most sighted species of Mediterranean sharks (Fig. 1A). For each species, we fitted a generalized linear model to the number of records per year, also controlling for a proxy of observation effort via an offset parameter. We quantified this proxy as the total number of sightings of any shark species recorded in the same year in the Mediterranean area. This approach assumes that one of the most critical factors boosting or decreasing the detection rate of species from opportunistic data is observation effort and the capability of people to communicate records through social media. Without an effective and precise observation effort index, we assumed that its effect would have impacted all species in the dataset. Hence, we factored out this process out by essentially looking at the relative trends of the focal species. This observer-oriented approach has been largely tested for opportunistic dataset analysis (Milanesi et al. 2020, Martino et al. 2021). Models were fit by using a Poisson, quasi-Poisson, and negative binomial (in the case of overdispersed data) distribution with a logarithm link function. The model structure was:

$$\log(Y_i) = a + b[\text{Year}]_i + \text{offset}(\log[\text{obs.eff}]_i) + \varepsilon_i \quad (1)$$

where Y_i is the number of sightings in the i^{th} year, a and b are the intercept and the slope respectively, $\log[\text{obs.eff}]_i$ is the offset parameter for the i^{th} year, log-transformed to maintain the same scale of the response variable, and ε_i is the error term for the i^{th} observation.

An exploratory data analysis of the dates on which photos were taken showed heterogeneous patterns in the latitudinal variation of the sightings across seasons in 4 different pelagic shark species: common thresher *Alopias vulpinus*, shortfin mako, blue shark, and basking shark. To test the significance of the differences that emerged, we fitted an ANOVA-type model with season as the experimental factor. The model was structured as:

$$Y_{ij} = \beta_0 + \beta_j\,[\text{Season}]_j + \varepsilon_{ij} \quad (2)$$

where Y_{ij} is the latitude of the i^{th} record in the j^{th} season, β_0 is the general average, β_j are effects for the j^{th} season, [Season] is a factor with 4 levels ($j = 1, \ldots, 4$), and ε_{ij} is the error term for the i^{th} observation in each season j. To properly estimate the model, a corner point approach was adopted setting 'Summer' as the reference level to test the significance of the difference between summer and the other seasons.

3. RESULTS

A total of 1168 records belonging to 37 different shark species were collected from the Mediterranean Sea between 1946 and 2020 (Table 1). The 5 most reported species were bluntnose sixgill shark *Hexanchus griseus* (23%, n = 273 photos), blue shark (18%, n = 212), shortfin mako (8%, n = 94), basking shark (8%, n = 91), and thresher shark (6%, n = 77). Carcharhiniformes was the most-reported order, with a total of 399 photos (34%). For 91 photos (7.79%), we were only able to recognize the sharks at the genus (83 records, 7.1%) or family level (8 records, 0.68%). The most challenging group for tax-

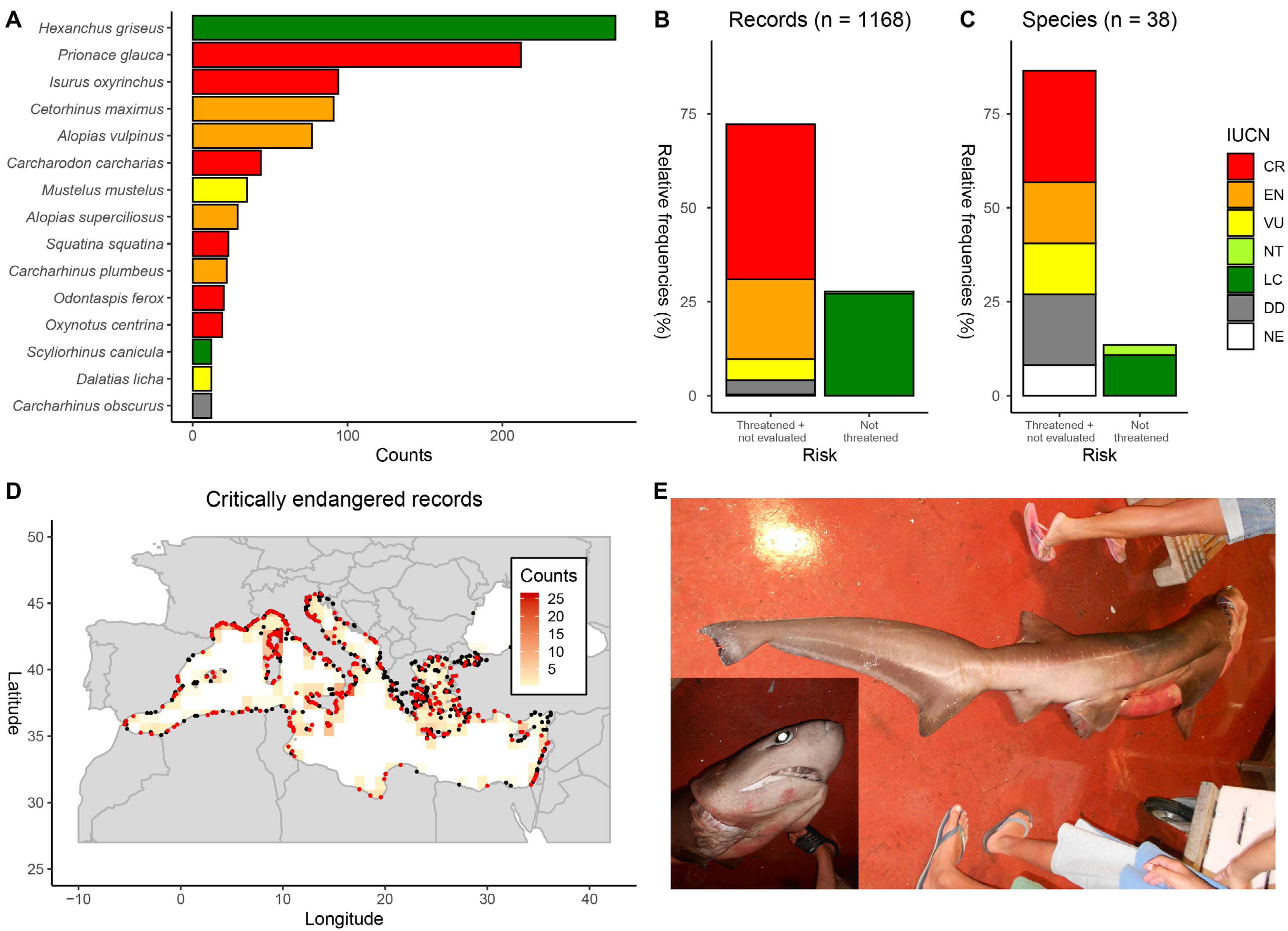

Fig. 1. (A) Fifteen most frequent Mediterranean shark species with their relative conservation status according to the IUCN Red List (see color key in panel C; abbreviations are defined in Table 1). Relative frequency of (B) records and (C) species related to the IUCN regional assessment. (D) Distribution of the records for CR species (red dots) among all records (black dots); over-imposed pixels show the cumulative count of CR records per unit area. (E) Example of a photo record of *Hexanchus griseus* from the sharkPulse database (photo credit: Azzurra Bastari)

Table 1. Summary of shark records (n = 1168) from sharkPulse in the Mediterranean Sea. IUCN categories from the Mediterranean assessment (Dulvy et al. 2016, Walls & Dulvy 2020) are DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered; CR: Critically Endangered; NE: Not Evaluated

Records	Counts	IUCN
Hexanchiformes	**291**	
Hexanchus griseus	273	LC
Heptranchias perlo	8	DD
Hexanchus nakamurai	6	DD
Hexanchus sp.	4	
Lamniformes	**377**	
Isurus oxyrinchus	94	CR
Cetorhinus maximus	91	EN
Alopias vulpinus	77	EN
Carcharodon carcharias	44	CR
Alopias superciliosus	29	EN
Odontaspis ferox	20	CR
Lamna nasus	7	CR
Alopias sp.	7	
Lamnidae	6	
Odontaspididae	2	
Carcharhiniformes	**399**	
Prionace glauca	212	CR
Carcharhinus sp.	47	
Mustelus mustelus	35	VU
Carcharhinus plumbeus	22	EN
Mustelus sp.	14	
Carcharhinus obscurus	12	DD
Scyliorhinus canicula	12	LC
Galeorhinus galeus	10	VU
Scyliorhinus stellaris	6	NT
Carcharhinus brachyurus	6	DD
Galeus melastomus	4	LC
Carcharhiniformes		
Sphyrna zygaena	3	CR
Carcharhinus altimus	2	DD
Carcharhinus falciformis	2	NE
Mustelus punctulatus	2	VU
Sphyrna sp.	2	
Carcharhinus brevipinna	1	NE
Carcharhinus limbatus	1	DD
Mustelus asterias	1	VU
Sphyrna lewini	1	NE
Squaliformes	**60**	
Oxynotus centrina	19	CR
Dalatias licha	12	VU
Centrophorus cf. *uyato*	10	CR
Squalus blainville	10	DD
Squalus acanthias	3	EN
Squalus sp.	3	
Centrophorus sp.	1	
Etmopterus spinax	1	LC
Somniosus rostratus	1	DD
Squatiniformes	**36**	
Squatina squatina	23	CR
Squatina sp.	5	
Squatina aculeata	4	CR
Squatina oculata	4	CR
Echinorhiniformes	**5**	
Echinorhinus brucus	5	EN

onomic identification was *Carcharhinus* spp., for which only 50% of the records (47 images) could be identified at the species level. Among the 8 records classified to the family level, 6 were Lamnidae, and 2 were Odontaspididae (sand sharks). Although there are 2 sand shark species in the Mediterranean Sea, *Carcharias taurus* and *Odontaspis ferox*, all sharkPulse records of this family identified at the species level (n = 20) were *O. ferox*.

In general, our data showed good coverage of the Mediterranean shark species diversity. Only 5 of the 40 species assessed in the last IUCN Mediterranean assessment (Dulvy et al. 2016, Walls & Dulvy 2020) were not present in our database: *Galeus atlanticus*, *C. taurus*, *Isurus paucus*, *Centroscymnus coelolepis*, and *Somniosus rostratus*. Conversely, we had sightings of 3 rare species not assessed by the IUCN in the Mediterranean: *Carcharhinus brevipinna*, *Carcharhinus falciformis*, and *Sphyrna lewini*.

Among the 15 most recorded species, 12 were threatened (6 Critically Endangered, CR; 4 Endangered, EN; and 2 Vulnerable, VU), 2 were Least Concern (LC), and 1 was Data Deficient (DD) (Fig. 1A). Of our photo records, 72% were threatened (68%) or DD species (4%); the remaining were either LC (27%) or not evaluated (NE) (1%). Among the threatened species, 41% were CR (Fig. 1B). The proportion of DD and NE species was higher when summarized in terms of species than when broken down in terms of records (Fig. 1C). Areas with a high frequency of CR records were identified around Corsica, in the Gulf of Lion, around Malta, and near the Strait of Messina in Sicily (southern Italy; Fig. 1D).

Annual records increased for all species since the beginning of our series (Fig. A1 in the Appendix). This was expected given our recent targeted effort in collecting sightings and the nature of our data, coming prevalently from online sources and especially social networks, which have expanded in use just over the last decade. However, when trends were analyzed in relative terms and for the most abundant species, statistically significant trajectories were estimated for only 2 of the 5 species analyzed (Fig. 2). *H. griseus* showed one of the steepest increases of

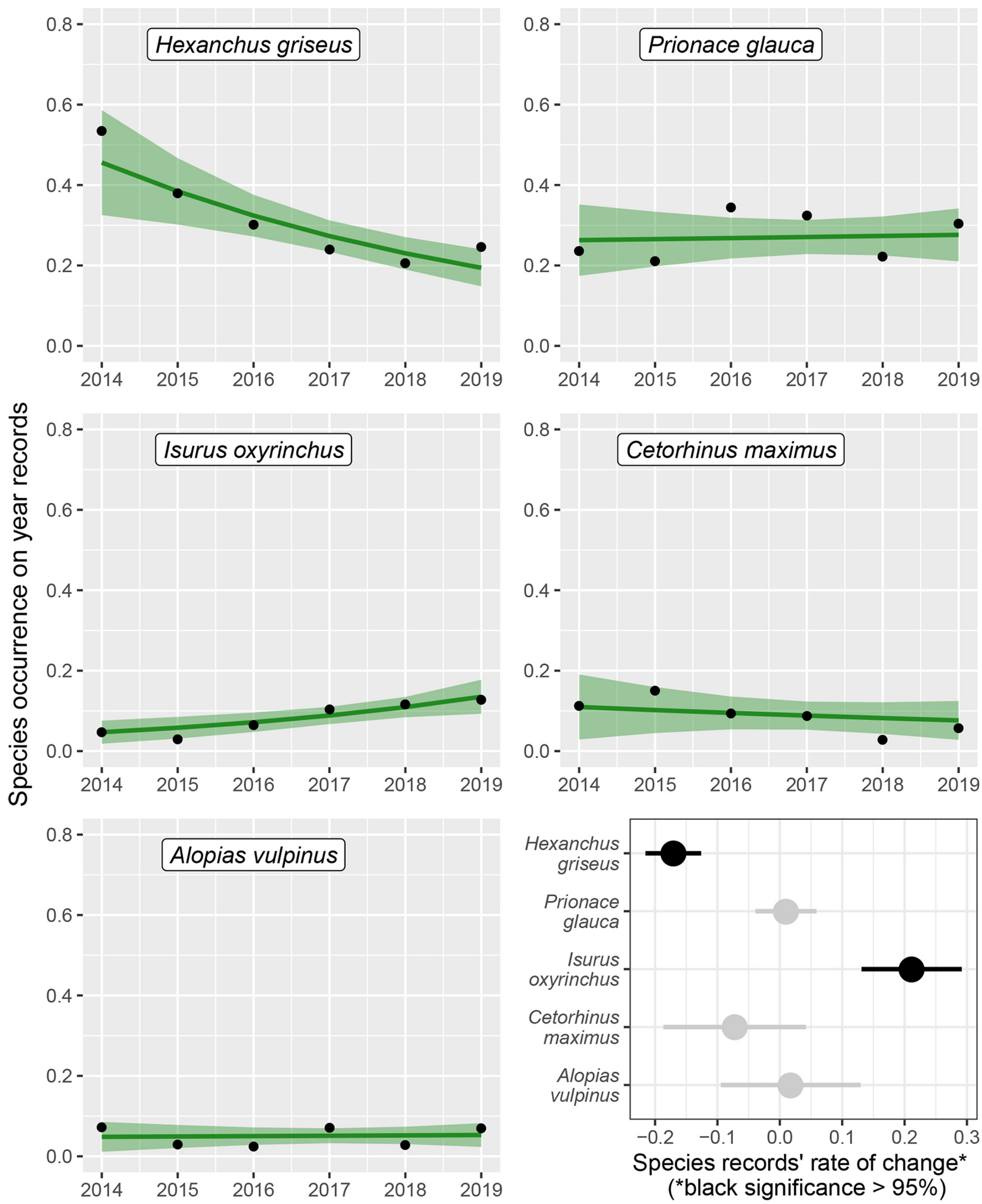

Fig. 2. Estimated trends in sighting rate for *Hexanchus griseus*, *Prionace glauca*, *Isurus oxyrinchus*, *Cetorhinus maximus*, and *Alopias vulpinus* between 2014 and 2019. The green buffer represents the confidence interval, while the black dots are the observed sighting rates (expressed as the number of sightings of the focal species per number of sightings of all shark species; see Section 2.2 for details)

unstandardized records followed by a −49.5% (range −41.6 to −53.9%) change in standardized relative abundance, whereas *I. oxyrinchus* kept increasing also in relative terms (+133%; range +78.1 to +358%) in the 5 years analyzed. Both thresher and basking sharks showed very low sighting rates with no significant trends. Finally, *P. glauca* had a steep increase in annual records over time, leading to the second-highest sighting rate among all species. However, no significant recent trend emerged when records were analyzed in relative terms. The fitted deviance obtained by the model for each species is shown in Table 2.

The geographic distribution of the records showed deviations from the published IUCN species geographic ranges (Fig. 3). *Dalatias licha*, *Echinorhinus*

Table 2. Generalized linear model statistics and fitted deviance for sighting rate trends tested in 5 Mediterranean shark species. **Bold** p-values indicate a significant difference at the 95 % confidence level

Species	Estimate	SE	p	Fitted deviance
Hexanchus griseus	−0.1708	0.0446	**0.0001**	0.762
Prionace glauca	0.0098	0.0489	0.842	0.006
Isurus oxyrinchus	0.2113	0.0803	**0.008**	0.73
Cetorhinus maximus	−0.0724	0.1142	0.526	0.038
Alopias vulpinus	0.0176	0.1121	0.876	0.004

brucus, *Heptranchias perlo*, *Hexanchus griseus*, *Oxynotus centrina*, and *P. glauca* occurred beyond the extent of occurrence identified by the IUCN Red List assessments (Dulvy et al. 2016, Walls & Dulvy 2020), extending in the Eastern Mediterranean Sea. Records for *Alopias superciliosus* were prevalent in this sector. Up to 2016, the presence of this species in the eastern Mediterranean Sea was still uncertain for the IUCN (Walls & Soldo 2016a). Similarly, *Carcharhinus obscurus* had 12 sharkPulse records in the Eastern Mediterranean Sea, even though the IUCN did not consider it a Mediterranean resident up to 2019 (Rigby et al. 2019), and the consensus on its presence has been ambivalent in previous literature

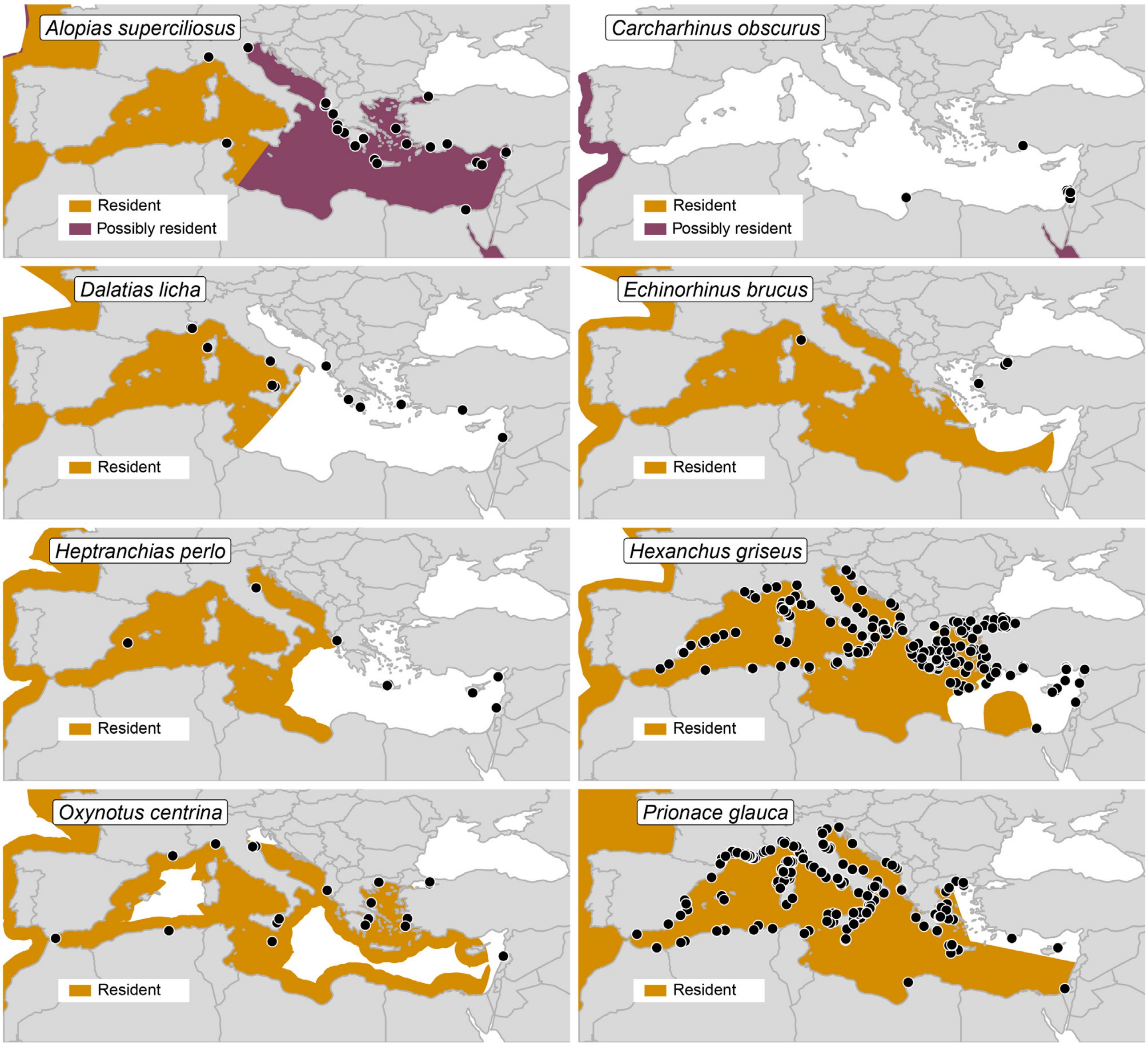

Fig. 3. IUCN geographical range and the distribution of our sharkPulse records

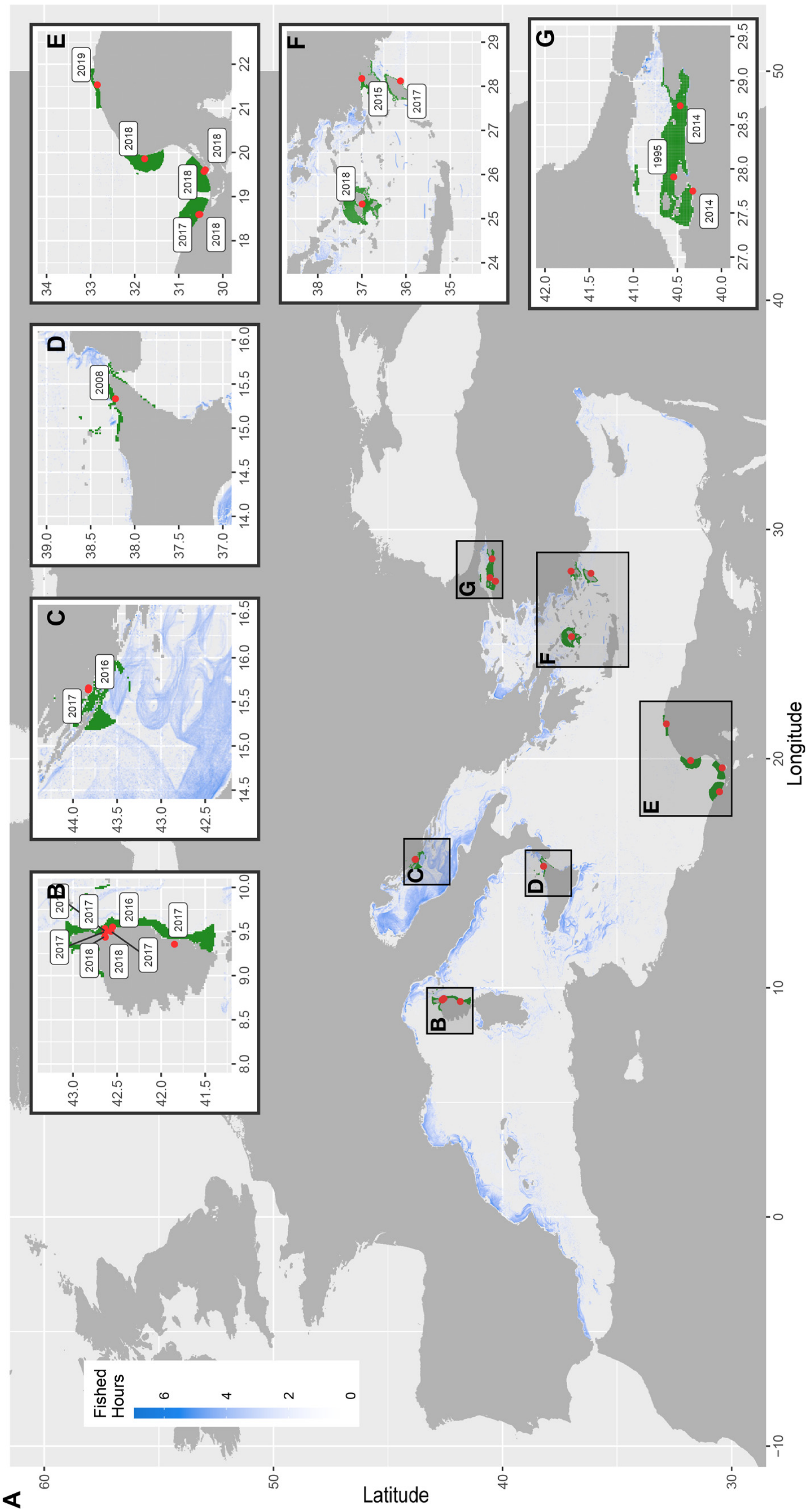

Fig. 4. Records of distribution, bathymetric ranges, and fishing pressure on the angelshark *Squatina squatina*, a rare and Critically Endangered demersal species. Fishing effort (average fished hours per 0.01° lat./long. on a logarithmic scale) for the year 2017 (blue) as reported in the Global Fishing Watch Database. Red dots are angelshark sighting locations, and the green polygons show the likely leftover patches of occurrence for the species within the Mediterranean basin (see Section 2)

(Capapé et al. 1979, Fergusson & Compagno 2000). The species is commonly observed in Israel and recently became officially included in Mediterranean faunal lists (Zemah-Shamir et al. 2019, Serena et al. 2020).

For the angelshark, a rare and heavily impacted CR species, we used the detected records to identify potential strongholds that could be taken as conservation opportunities and areas to focus on for recovery programs (Fig. 4). These strongholds would be confined in the eastern Adriatic Sea, the northeastern coast of Corsica, the Aegean and Marmara Seas, and some coastal areas of Libya. We predicted that the relict distribution of Mediterranean angelsharks would span over a surface of 20 824 km^2, which represents 4.82 % of the suitable area for the species and only 0.83 % of the entire surface covered by the Mediterranean Sea.

Analyzing the spatio-temporal distribution of our sighting records, we identified latitudinal shifts in the records' distribution of the most abundant pelagic species (Fig. 5, Table 3). Blue shark records generally shifted southward during fall (−2.15 ±

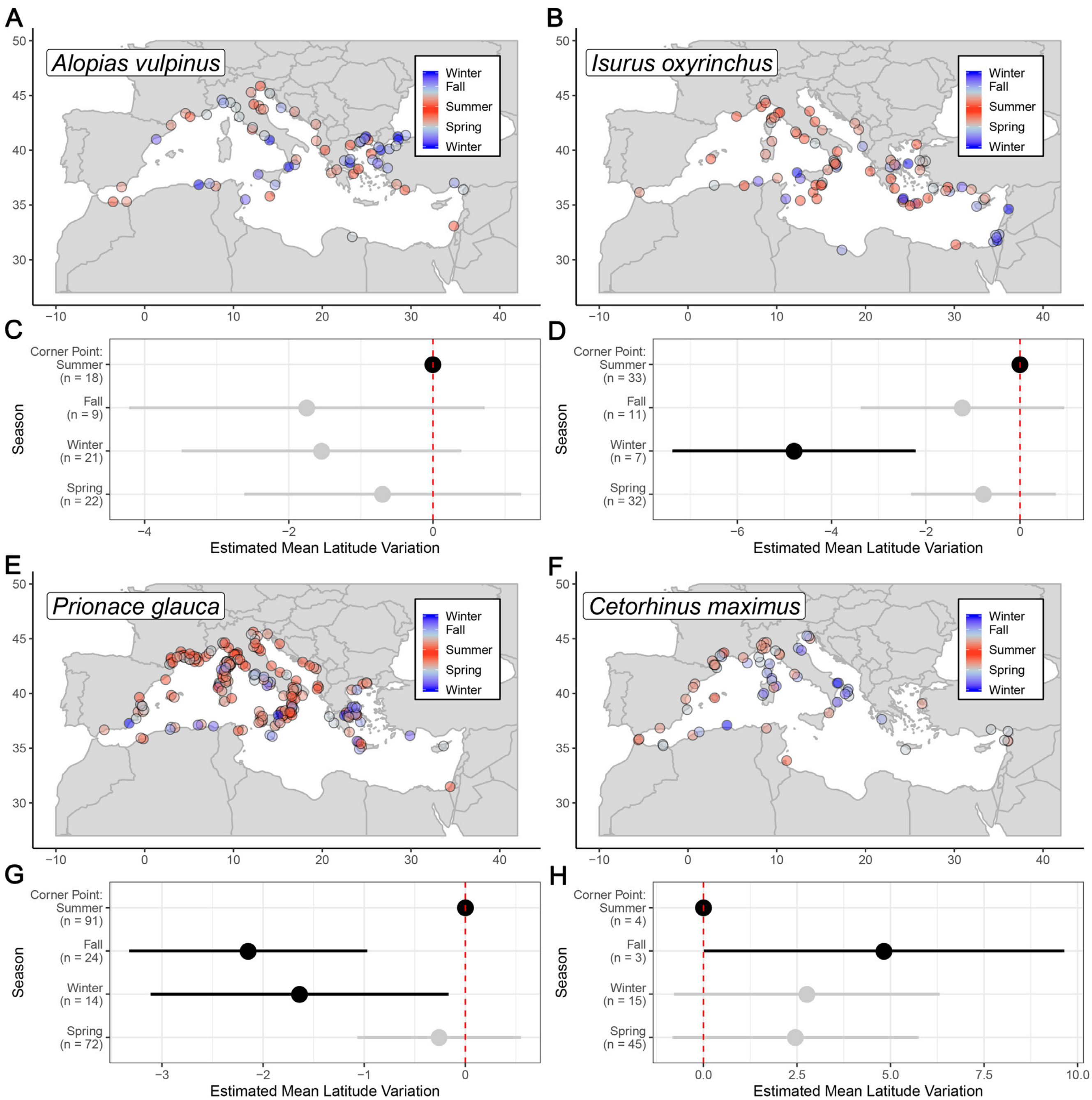

Fig. 5. Latitudinal changes in records distribution across seasons in 4 pelagic shark species: common thresher *Alopias vulpinus*, shortfin mako *Isurus oxyrinchus*, blue shark *Prionace glauca*, and basking shark *Cetorhinus maximus*. Details on statistics are shown in Table 3. Colors for dots and CI represent different significance levels (black: 95% significance; grey: no significance). The red dashed line represents the corner point mean that is set to zero to better show the seasonal effects

0.59 latitude degrees) and winter (−1.64 ± 0.75 latitude degrees, Fig. 5E,G). Similarly, shortfin mako records also significantly shifted southward in winter (−4.80 ± 1.30 latitude degrees, Fig. 5B,D). Conversely, basking shark records were distributed at higher latitudes during fall (mean latitude shift, +4.83 ± 2.41 latitude degrees, Fig. 5F,H). Hotspots of blue shark sightings in the warm seasons (spring and summer) were in southern France, Corsica, Tuscany (Italy), and the western Ionian Sea, while in cold seasons (fall and winter), most records were located in the central Aegean Sea (Fig. 5E). Thresher sharks showed a similar pattern. They were mostly sighted in southern France and in the

Table 3. Statistics and p-values for the latitudinal changes in the distribution of the records in the different seasons for 4 Mediterranean shark species. **Bold** p-values indicate a significant difference at the 95 % confidence level

Species	Season	Estimate	SE	*t*	p	CI lower	CI upper
Alopias vulpinus	Corner point: summer	41.0592	0.7132	57.5729	0.0000	39.6353	42.4831
	Mean fall variation	−1.7499	1.2352	−1.4166	0.1613	−4.2161	0.7164
	Mean spring variation	−0.6991	0.9616	−0.7270	0.4698	−2.6191	1.2208
	Mean winter variation	−1.5473	0.9719	−1.5921	0.1161	−3.4877	0.3931
Isurus oxyrinchus	Corner point: summer	38.9483	0.5428	71.7599	0.0000	37.8680	40.0287
	Mean fall variation	−1.2205	1.0855	−1.1243	0.2643	−3.3811	0.9402
	Mean spring variation	−0.7778	0.7736	−1.0056	0.3177	−2.3176	0.7619
	Mean winter variation	−4.7972	1.2974	−3.6974	**0.0004**	−7.3797	−2.2147
Prionace glauca	Corner point: summer	40.8784	0.2729	149.8171	0.0000	40.3403	41.4165
	Mean fall variation	−2.1477	0.5973	−3.5959	**0.0004**	−3.3256	−0.9699
	Mean spring variation	−0.2589	0.4105	−0.6307	0.5290	−1.0685	0.5507
	Mean winter variation	−1.6392	0.7472	−2.1936	**0.0294**	−3.1128	−0.1655
Cetorhinus maximus	Corner point: summer	38.0882	1.5781	24.1350	0.0000	34.9346	41.2419
	Mean fall variation	4.8272	2.4106	2.0025	**0.0495**	0.0099	9.6445
	Mean spring variation	2.4607	1.6468	1.4942	0.1401	−0.8302	5.7515
	Mean winter variation	2.7637	1.7761	1.5560	0.1247	−0.7856	6.3130

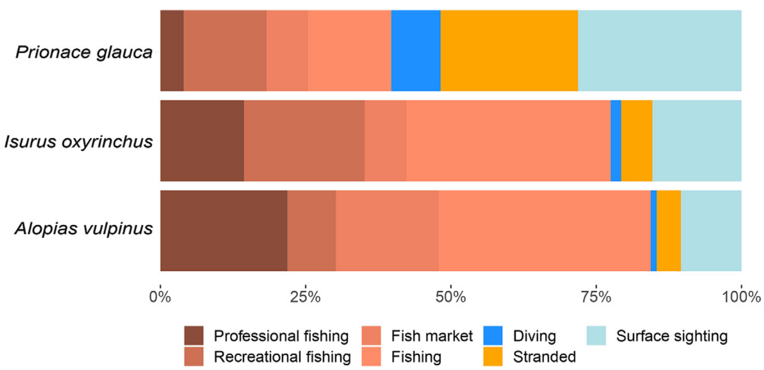

Fig. 6. Type of observation among the records of some pelagic shark species: blue shark *Prionace glauca*, common thresher *Alopias vulpinus*, and shortfin mako *Isurus oxyrinchus*. When a record is categorized as 'fishing', it means it was not possible to reconstruct whether the event was related to professional or recreational fishing

northern Adriatic Sea during the warm period. Conversely, in the coldest seas, records were more abundant in the Aegean and the Marmara Seas (Fig. 5A). Similarly, in the cold period, shortfin makos were mainly found in the Aegean Sea and in the southern part of the Mediterranean Sea, while in the warm period, they were also present northern sectors (Ligurian, Tyrrhenian, and Adriatic Seas, Fig. 5B).

Most of our shortfin mako records (78 %) and common thresher records (84 %) were related to fishing activities (Fig. 6). This percentage was lower for blue sharks (39 %), for which there was a relevant number of stranded specimens (24 %) and direct observations of live animals swimming close to the surface (28 %).

Of blue shark and shortfin mako records, 41 and 75 %, respectively, were immature specimens. Immature shortfin makos (<200 cm) were found throughout the Mediterranean Sea, with the exceptions of southern Spain and the southeastern Mediterranean Sea. Blue shark immatures (<120 cm) were mainly seen in southern France, Italy, and the northern Aegean Sea (Fig. 7A). Among the immature blue sharks, YOY records (12 % of all blue shark records) were mainly found in spring and summer, with a peak in June and July. These records were in Southern France, the northern Tyrrhenian and Ligurian Seas, and in the northwestern Ionian Sea (Fig. 7B). In addition, 4 cases of blue shark parturition were reported in the northern Ionian Sea (Table 4).

Table 4. Cases of spontaneous parturitions recorded in stranded blue sharks *Prionace glauca*. Numbers refer to Fig. 6. CS: Cosenza; TA: Taranto

No.	Date	Location
1	16 May 2017	Villapiana (CS)
2	12 June 2017	Castellaneta marina (TA)
3	18 April 2019	Ginosa Marina (TA)
4	20 May 2019	Chiatona (TA)

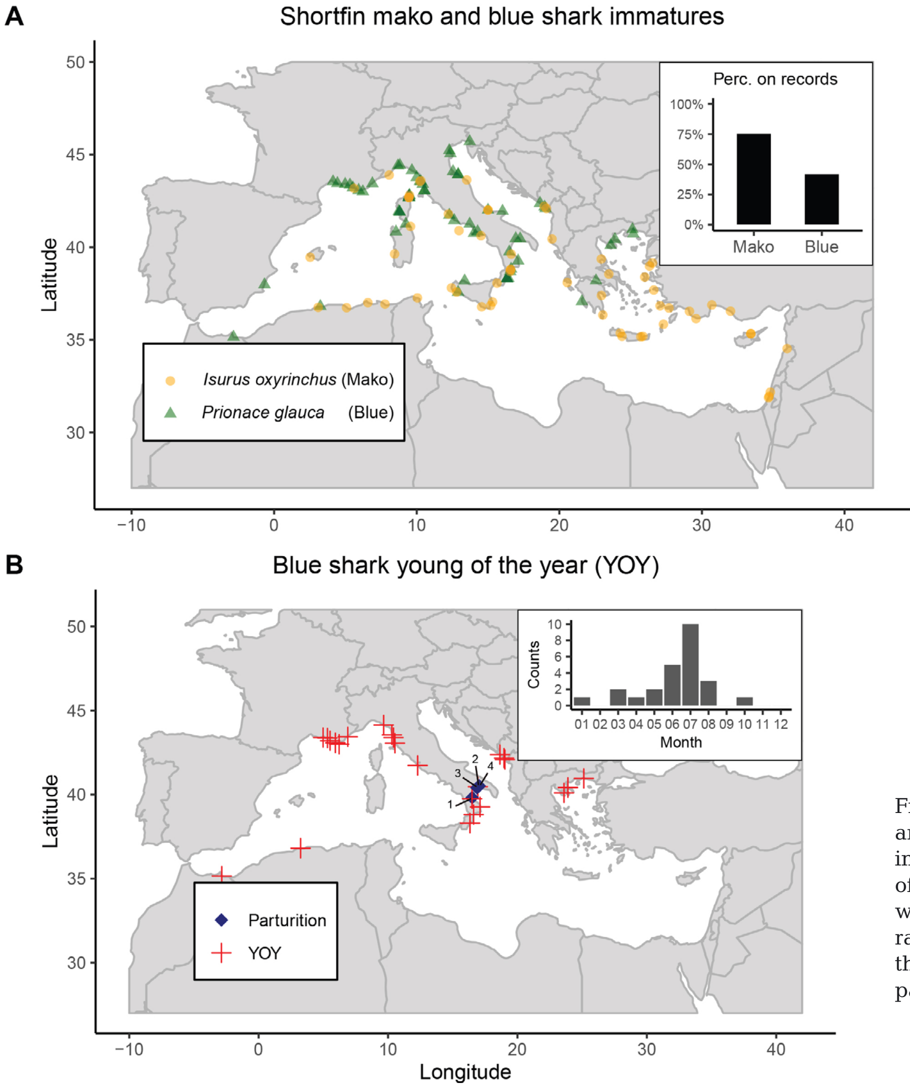

Fig. 7. (A) Blue shark *Prionace glauca* and shortfin mako *Isurus oxyrinchus* immature distribution and percentage of the records from which size class was detectable. (B) Spatial and temporal distribution of blue shark young of the year (YOY); blue diamonds mark parturition sites, numbers refer to Table 4

4. DISCUSSION

There is a critical need for increased data collection on sharks in the Mediterranean Sea. Here we summarized patterns emerging from sharkPulse, a new crowdsourcing initiative compiling shark photo-sightings around the world. These records are obtained through unsolicited submissions or directly sourced from online repositories, social networks, and citizen science initiatives. These data, from the Mediterranean Sea, outlined abundance and distribution patterns of almost all sharks listed in the region. While this outline was not intended to produce robust spatio-temporal trends in the abundance of the recorded populations, our intention was to highlight emerging patterns to guide more focused and deeper investigations. These data identified crucial areas where CR species are still occurring, underpinning challenges and opportunities for future conservation and recovery plans; enlarged the spatial and temporal scale of biological processes previously hypothesized for large pelagic species with more restricted observations (geographically and temporally); and highlighted ongoing long-term and large-scale trends deserving further and more targeted investigations.

The bluntnose sixgill shark *H. griseus* was the most frequently recorded species in our database (Fig. 1, Table 1). Its number of sightings went through one of the steepest increases over the last 20 yr, followed by a significant decline both in absolute and relative terms between 2014 and 2019. These trends were possibly driven by a spatial expansion and deepening of Mediterranean fisheries and thus need to be refined with efficient estimates of observation effort. Nonetheless, they call for deeper investigations into possible spatial ecological niche expansion and population growth. *H. griseus* is a demersal species that, in the Mediterranean Sea, has been reported as bycatch of several fishing gears (e.g. bottom trawls and longlines; Capapé et al. 2004, Kabasakal 2013, Serena 2021). In our database, most *H. griseus* records (70%) came from fish markets or landings, but around 12% were photographed on board fishing vessels. The large size of *H. griseus* also attracts public attention, making the species easily detectable through online newspapers and social networks (Capapé et al. 2004, Ben Amor et al. 2019, Giovos et al. 2020). The IUCN classifies *H. griseus* as LC in the Mediterranean, mostly because of its wide depth range that exceeds fisheries limits and a lack of long-term studies on population trends or size, in the Mediterranean Sea (Capapé et al. 2003, 2004, Celona et al. 2005, Kabasakal 2013, Ben Amor et al. 2019) and elsewhere. Conversely, in the 19th century, *H. griseus* was considered rare in the Mediterranean sea, except for Sicily (Doderlein 1879). We propose that this predator may have benefitted from the loss of other large predatory sharks in the area (Ferretti et al. 2008), both because of reduced competition and reduced predation. *H. griseus* may have expanded its ecological niche previously occupied by other large sharks in more coastal superficial waters, a pattern already observed with another ecologically similar cow shark (the broadnose sevengill shark *Notorynchus cepedianus*), in response to short-term declines of white sharks in South Africa (Hammerschlag et al. 2019). While the expanding Mediterranean fisheries in deeper waters (Celona et al. 2005, Ferretti et al. 2008, Kabasakal 2013) may have contributed to a large number of sightings in the last 2 decades, its continued impact on the population may have eventually eroded any compensatory population response to changing interspecific interactions, as suggested by the recent significant decline in relative sighting rate (Fig. 2). Similar compensatory population increases eventually damped down by the effect of intensive exploitation have been demonstrated in other ocean sectors (Baum & Worm 2009, Ferretti et al. 2010).

Large predatory sharks such as shortfin makos and blue, basking, thresher, and white sharks were also abundant in our records. These are charismatic species that attract public attention and consequently are more likely to appear in social networks and be disproportionately more abundant in our database. Among these species, the shortfin mako was the only one increasing in relative abundance in our data (Fig. 2). The spatial and temporal distribution of blue, shortfin mako, and basking shark records matched seasonal movements reported in the North Atlantic (Kohler et al. 2002, Vandeperre et al. 2014, Doherty et al. 2017) with independent data (Fig. 5, Table 3). These shifts are in line with the wide-ranging and migratory behavior of pelagic sharks (Stevens 1990) driven by foraging, thermoregulation, and reproductive needs (Skomal et al. 2009), although seasonal changes of observation effort (i.e. spatio-temporal patterns of tourism) may also play a role. Defining standardized seasonal patterns of distribution with efficient indices of observation effort is crucial for characterizing the ecology of these species in the basin and then planning efficient conservation and management actions.

Taxonomic resolution on our data was high. Most (92%) of the records were identified to the species level. This is remarkable, as one of the greatest issues of fisheries-dependent data on sharks is low taxonomic resolution, especially in the Mediterranean Sea (Cashion et al. 2019, Giovos et al. 2021b). Our data collection system outperformed other data streams conventionally used in research, management, and conservation. For example, >75% of FAO landings are not identified at the species level (Cashion et al. 2019). Some species identification challenges occurred for the genus *Carcharhinus* and the families Lamnidae and Odontaspididae. For lamnids, in some cases social network or on-line news sightings of young shortfin makos were confused with juvenile great white sharks (Fergusson 2002, Morey et al. 2003, Bargnesi et al. 2020b). For *Carcharhinus* spp., 54% of the records could not be identified at the species level, reflecting a common problem when collecting requiem shark data from fisheries and scientific fishing surveys (Baum et al. 2003, Baum & Blanchard 2010, Romanov et al. 2010, Serena et al. 2014).

The majority (73%) of our records belonged to threatened species (Fig. 1B). This is expected in the Mediterranean Sea, which has the highest proportion of threatened shark species in the world (Walls & Dulvy 2020). It also suggests that sharkPulse can act as an efficient and inexpensive real-time monitor of shark sightings over time. Conventional data collection processes become more difficult and expensive as species decline in abundance (Sgarbi et al. 2020). In our data, instead, the propensity to report and communicate sightings may increase as species become rarer and more endangered. This aspect must be considered when standardizing these records to produce abundance indices. Nonetheless, records of CR species can identify strongholds of occurrence and consequently offer opportunities for applied conservation (Fig. 1D). Previous studies consistently identified some Mediterranean areas as shark biodiversity hotspots, and, consequently, priority areas for conservation. These included, among others, the Gulf of Gabes (Enajjar et al. 2015), the northern and central Adriatic Sea (Soldo & Jardas 2002, Cugini & De Maddalena 2003), and the Marmara Sea (Kabasakal & Karhan 2015). Of these areas, the Gulf of Gabes and the northern Adriatic Sea were also indicated as possible reproductive sites (Enajjar et al. 2015). Our data confirm these places as hotspots of endangered species' records and suggest that southern France, Corsica, the northern Tyrrhenian Sea, Malta, and Cyprus warrant further investigation into the local shark biodiversity (Fig. 1D).

The angelshark *Squatina squatina* is a CR species once abundant and widely distributed in the Mediterranean Sea and throughout the Northeast Atlantic (Ferretti et al. 2013, Fortibuoni et al. 2016, Lawson et al. 2020). Because of its critical conservation status, it is now the focus of multiple studies, data collection efforts, and conservation initiatives aimed at promoting its recovery in the region (Kabasakal & Kabasakal 2014, Akyol et al. 2015, Fortibuoni et al. 2016, Gordon et al. 2017, 2019, Giovos et al. 2019, Lawson et al. 2020). These efforts would benefit from a regional and unified monitoring scheme for the species. SharkPulse records confirmed the presence of *S. squatina* in multiple Mediterranean sectors and highlighted a very fragmented and restricted range. The species has a limited bathymetric distribution (0–50 m) and low mobility, and is heavily impacted by coastal fisheries (Fortibuoni et al. 2016). Accordingly, we projected remaining strongholds for the species in restricted sectors relatively less impacted by fishing (Fig. 4). Our fishing effort index based on Automatic Identification System (AIS) data (Kroodsma et al. 2018) may have underrepresented the actual level of fishing effort in the regions, especially in coastal waters, given that the European Commission mandates AIS for fishing vessels over 24 m whereas up to 85% of the European fishing vessels in the Mediterranean Sea are <12 m (Quetglas et al. 2016, Ferrà et al. 2020); nevertheless, these sectors are hotspots of high shark biodiversity where other critically endangered species occur. Constant monitoring and simple spatial analyses, boosted by improved data collection and integration with environmental (e.g. depth, primary production, water salinity, temperature) and human impact data layers, can identify threats impacting local populations, estimate underlying population processes, and spot critical habitats where immediate action is needed. These efforts could inform designating marine protected areas or fisheries exclusion zones to avoid the extinction of this and other critically endangered species.

Our records would update the IUCN geographical range maps of 8 species of large sharks (Fig. 3). The IUCN defines geographical ranges by using the extent of occurrence (area within the outermost geographic limits of the species' occurrence), and the area of occupancy (area over which the species actually occurs; Gaston & Fuller 2009). In the Mediterranean Sea, these ranges seem loosely defined as the area facing countries where the species have been recorded (Dulvy et al. 2016), even though source records and information are seldom reported explicitly (Jorgensen et al. 2022). SharkPulse data would transition this approach toward a more direct, transparent, and data-informed method (keeping in mind the caveats associated with opportunistic records). Our data would expand the geographic range of *Dalatias licha* in the Eastern Mediterranean Sea by confirming bibliographic records from Greece (Papakonstantinou 1988, Chatzispyrou et al. 2019), Turkey (Ergüden et al. 2017), Cyprus (Giovos et al. 2021a), and Israel (Golani 1986), and adding new records in Albania and Lebanon. Similarly, *Heptranchias perlo* is confirmed in Greece (Giovos et al. 2020), Turkey (Başusta 2016), and Egypt (Shaban & El-Tabakh 2019), and extended to Crete, Lebanon, and Turkey. *Hexanchus griseus* is confirmed in the southern coast of Turkey (Kabasakal 2006) and Syria (Alkusairy & Saad 2018) and extended to Cyprus, Lebanon, and Egypt. The rare, deep-water shark *Echinorhinus brucus* is confirmed in Turkish waters (Kabasakal & Bilecenoglu 2014). *Oxynotus centrina* is confirmed in the Marmara Sea (Kabasakal 2015b). *Prionace glauca* must be considered widely present throughout the Mediterranean Sea (Megalofonou et al. 2009), including Turkish waters. *Alopias superciliosus* was considered rare in the Eastern Mediterranean Sea (Kabasakal & Karhan 2008). However, 26 sharkPulse records from this area would justify updating its status from 'possibly resident' to 'resident', as also indicated by Lanteri et al. (2017) and Kleitou et al. (2017). *Carcharhinus obscurus* was recently documented from Lebanon (Lteif et al. 2014) and Israel (Zemah-Shamir et al. 2019), with seasonal occurrences. Our 12 records add further evidence that this species occurs in the Mediterranean Sea and is possibly resident in its eastern part.

A major threat for Mediterranean sharks is bycatch in both professional (Cavanagh & Gibson 2007, Ferretti et al. 2008, Carpentieri et al. 2021) and recreational fishing activities (Megalofonou et al. 2000, 2005a,b, Garibaldi 2015, Dulvy et al. 2016). Our data confirm this aspect, especially for pelagic species. Most of our shortfin mako and common thresher records (73–84%) came from fishing activities (Fig. 6). Mediterranean fisheries have severely impacted these populations historically (Ferretti et al. 2008), although the current exposure of these species to fishing is still unclear. This is particularly true for small-scale fisheries, which are less efficiently monitored by remote sensing technology (Kroodsma et al. 2018) and institutional data collection programs than industrial fisheries. Estimating the overlap between shark distribution and fisheries in the Mediterranean Sea (Queiroz et al. 2019, White et al. 2019) is now paramount to prevent further declines and to plan recovery programs. This region is also lagging in terms of available shark telemetry data, and the use of opportunistic data may be a feasible alternative for estimating shark exposure to current fishing activities.

The Mediterranean Sea is an important ecoregion for the reproduction of many large, broad-ranging marine fishes (Aalto et al. 2021). Blue shark nursery areas have been suggested in the northern Adriatic Sea and Ionian Sea (Megalofonou et al. 2009). Here, parturition events, observed along the Ionian coasts and documented by videos (Table 4), reinforced this hypothesis. In our records, YOY blue shark records occurred in the Ligurian Sea and off southern France (Fig. 7B), where it is also possible to hypothesize other nursery areas. However, not all sectors where these life stages are observed should be directly classified as nursery areas. Shark nurseries can be defined by 3 criteria (Heupel et al. 2007): (1) YOY are more commonly encountered in the area than in others, (2) YOY have a tendency to remain in or return to the area for extended periods, and (3) the area is repeatedly used across years. Our data, refined with observation effort, would support the first criterion and identify areas where further telemetry studies could test the remaining condition. YOYs present in our study were observed from March to August, with a peak in June–July (Fig. 7B). A high percentage of immatures was observed for both blue sharks and shortfin makos (Fig. 7A). For shortfin makos, immatures represented 75% of the records, suggesting that the Mediterranean Sea may play an important role in the juvenile stages of this species. Immature shortfin makos have been previously observed in the Adriatic Sea (Udovičić et al. 2018) and Turkey (Kabasakal 2015a), but proof of the presence of nurseries for this species is still not available. Continuous monitoring could clarify which areas are used by immatures and YOYs to apply specific and proper *in situ* conservation measures such as fisheries-restricted zones or other management actions (temporary or permanent spatial closures, technical gear modifications, or effort control measures) targeted to avoid the catch of these life stages. Furthermore, population structure and interconnections with the Atlantic Ocean for blue sharks and shortfin makos are yet to be completely understood. Genetic analyses revealed some connectivity between the Mediterranean and the North-eastern Atlantic blue shark populations (Leone et al. 2017), but no connection has so far been demonstrated for shortfin makos, which should have a separate stock in the North Atlantic and one in the Mediterranean Sea (ICCAT 2019).

Although data standardization is still the major challenge when analyzing opportunistic records (McPherson & Myers 2009, Moro et al. 2020), these data can be used to explore and test ecological hypotheses formulated with more restricted and data-poor studies, especially for sharks for which conventional data are often limited and insufficient. Our study shows that opportunistic data, sourced through citizen science and new technologies, can represent an important source of information for rare and endangered shark species. These data can increase our understanding of their abundance and distribution, and threats that they are facing, providing useful information for both conservation and management. The Mediterranean Sea is an area with a large human pressure on shark populations, resulting in one of the world's highest percentages of locally endangered shark species. SharkPulse aims to become a real-time monitoring platform able to efficiently fill the data gap on threatened species, often emerging in several regional and global assessments on shark species (Jorgensen et al. 2022). This platform is in constant implementation and improvement, from refining methods of data acquisition to improving strategies to increase the taxonomic resolution of the collected data (i.e. increasing the reliability of species-specific classification even for challenging photographic material and taxonomic groups). Meanwhile, it can provide an open access data platform to scientists and conservation managers willing to leverage citizen science initiatives. These are expanding in the Mediterranean Sea, and several focus on sharks (Bargnesi et al. 2020b). It is now crucial to coordinate these initiatives at a regional level, developing an integrated network of ongoing projects with the scope of collecting and analyzing occurrence records of sharks. SharkPulse is working toward this direction with national focal points, which are promoting collaboration among other local and regional initiatives focusing on opportunistic collection of shark data. Creating a network of shark-related citizen science programs in the Mediterranean region is essential to efficiently collect robust and useful occurrence data. Hence, a stable, free, and open access system is required as the base of this kind of process, and sharkPulse meets all of these criteria.

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Appendix.

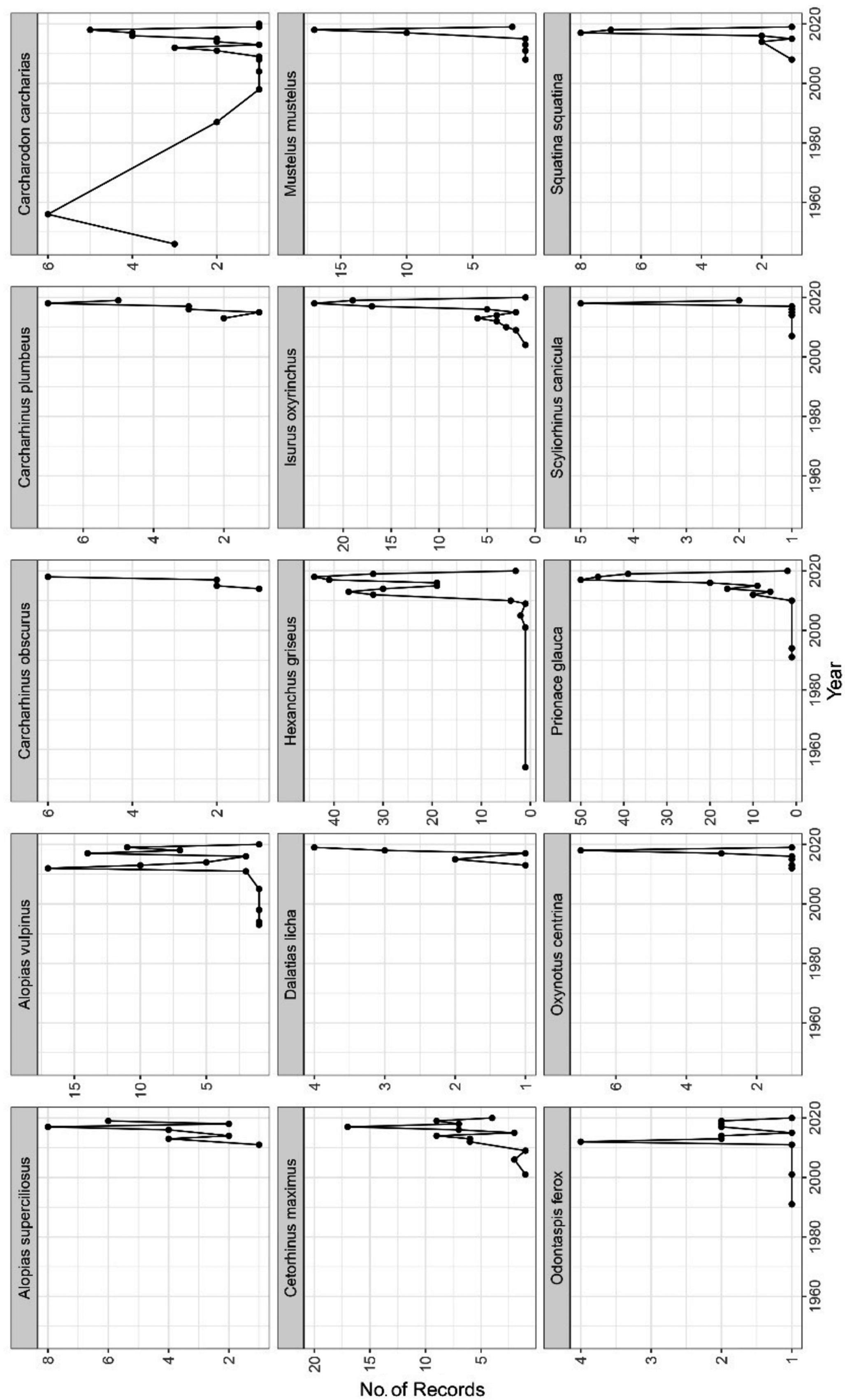

Fig. A1. Temporal trend in records of the 15 most commonly represented species in the SharkPulse database

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