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Breeding evidence and seasonality of the blue shark (*Prionace glauca*) on the northern Catalan coast

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Summary: Many shark species face serious threats that have generally led to a collapse in their numbers at a global scale. The blue shark (*Prionace glauca*) is one of the most by-caught large shark species in the Mediterranean Sea, where it has been classified as critically endangered. Despite the status of the species in this sea, little is known about its breeding areas. Here, we provide evidence that the Cape of Creus marine canyon and its surrounding areas are a blue shark mating, birthing and nursery area. We carried out a total of 170 chumming pelagic surveys from April to October in 2022, 2023 and 2024, with a total sampling effort of 933 h. In those surveys, we carried out 213 blue shark observations, including young of the year (n=10), some of them newborns, and adults (n=25), one of them a pregnant female. The encounter rate of blue sharks during periods of high adult and newborn presence was estimated at 0.42 individuals per hour, showing a significant seasonal concentration in this area. The peak presence of adults occurred between June and July, while that of newborns was observed in late June, overlapping with the peak of adults. We also registered two young of the year near the head of the Begur/La Fonera submarine canyon. A significant number of juveniles were also found in the study area, showing that this zone is also crucial for them. We conclude that the Cape of Creus, Lacaze-Duthiers and Begur/La Fonera submarine canyons are important areas for conservation of the blue shark in the western Mediterranean Sea and therefore emphasize the need for effective management and conservation strategies.

Keywords: *Chondrichthyes*; Cape of Creus; NW Mediterranean; reproduction; newborns; conservation.

Evidencia de la reproducción y estacionalidad de la tintorera (*Prionace glauca*) en el norte de la costa catalana

Resumen: Muchas especies de tiburón se enfrentan a serias amenazas, que en general las han llevado a un colapso de su número a escala global. La tintorera (*Prionace glauca*) es sin duda la especie más capturada accidentalmente en el Mediterráneo y, por ello, ha sido clasificada como "En peligro crítico". A pesar de su estatus en este mar, se sabe muy poco sobre sus áreas de reproducción. En este trabajo se aportan evidencias de que el cañón submarino del cabo de Creus y las áreas circundantes son una zona de apareamiento, parto y crianza de la tintorera. Se llevó a cabo un total de 170 jornadas de atracción de tiburones pelágicos entre abril y octubre de 2022, 2023 y 2024, con un esfuerzo total de muestreo de 933 h. En esas campañas, se realizaron 213 observaciones de tintoreras, incluidos crías del año (YOY) (n=10), algunas de ellas recién nacidas, y adultos (n=25), uno de los cuales una hembra preñada. La tasa de encuentro de tintoreras durante el período de presencia de adultos y recién nacidos fue de 0,42 por hora, lo que muestra una concentración estacional significativa en esta área. El pico de presencia de adultos se produjo entre junio y julio, mientras que la de recién nacidos se observó a finales de junio, solapándose con el pico de los adultos. También se registraron dos crías cerca de la cabecera del cañón submarino de Begur/La Fonera. Por otro lado, se observó un elevado número de ejemplares juveniles en el área de estudio, lo que demuestra que esta zona también es crucial para ellos. Se concluye que los cañones submarinos del Cabo de Creus, Lacaze-Duthiers y Begur/La Fonera son un área importante para la conservación de la tintorera en el Mediterráneo occidental y, por lo tanto, se enfatiza en la necesidad de adoptar estrategias de gestión y conservación efectivas.

Palabras clave: *Chondrichthyes*; Cabo de Creus; NO Mediterráneo; reproducción; recién nacidos; conservación.

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INTRODUCTION

Escalating anthropogenic activities have caused an increase in the pressure on marine ecosystems, impacting various marine species and leading to significant alterations in ecological dynamics (Worm et al. 2006, Christensen et al. 2014). These human-induced changes can intensely affect marine predators such as sharks (Myers and Worm 2003), whose populations have generally collapsed at a global scale (Dulvy et al. 2021). Sharks have an important role in ecosystems, and they can act as both apex predators and mesopredators (Dedman et al. 2024). In the Mediterranean Sea, factors such as overfishing and unintentional surface longline by-catch have been reported as the main causes of the above-mentioned collapse, especially in the case of large and medium-sized sharks (Cavanagh and Gibson 2007, Ferretti et al. 2008). Particularly in this sea, blue sharks (*Prionace glauca*) are the most by-caught large shark species (Biton-Porsmoguer and Lloret 2018, Nuez et al. 2021, Cimino 2022), being classified as critically endangered by the IUCN (Sims et al. 2016) after having suffered a severe decrease in their numbers. For instance, Dolfo et al. (2024) have shown that their effective population size (N_e) in this sea is currently extremely low, estimated at only 450–1480 breeding adults.

The blue shark is an epipelagic species that can display annual movements of hundreds to thousands of kilometres (Vandeperre et al. 2014, Druon et al. 2022, Poisson et al. 2024). Throughout the annual cycle, this shark species can aggregate in large numbers within relatively small areas for feeding and/or breeding purposes. Such areas of high-quality habitat are often selected differently between age and sex classes, depending on environmental parameters such as sea temperature and productivity (Druon et al. 2022).

The reproduction patterns of blue sharks are relatively well-known (e.g. Fujinami et al. 2017, Domingo et al. 2022). In this viviparous species, the reproduction cycle is generally annual, and the gestation period lasts approximately one year. In the Mediterranean Sea, births typically occur during a defined period between late spring and summer, while the birth season is loosely defined in other areas (Domingo et al. 2022). After the mating period, females can ovulate, copulate and gestate immediately. They also show a certain degree of fidelity to these areas, not only for giving birth but also for mating and feeding (Pratt and Carrier 2001, Domingo et al. 2022).

Though the reproductive cycle is well-known, there is limited knowledge about blue shark breeding areas in the Mediterranean Sea. Until recently, there were only a few locations in which some YOY (young of the year) or presumed pregnant females had been observed (Ćetković et al. 2019, Domingo et al. 2022, Mancusi et al. 2023). In studies on sharks that had been by-caught by fishing vessels, there were also a few observed individuals under 70 cm in length but practically no newborns (Megalofonou et al. 2009, Mancusi et al. 2023).

Recently, satellite-tagged blue sharks in the western Mediterranean Sea have been found to primarily concentrate in the Gulf of Lion and the waters in front of the northern Catalan coast (northwestern Mediterranean) between late spring and summer (Poisson et al. 2024). These authors pointed out that the presence of large juvenile females (some with fresh mating bite marks) and adult males in the area suggested reproduction activity. Although Poisson et al. (2024) did not provide direct evidence of blue shark reproduction in this area, they highlighted that the tagged sharks were present there between the period when mating and birth are expected to occur (Domingo et al. 2022). In this area, professional fishermen had also reported the capture of YOY individuals (Poisson et al. 2024). Moreover, Dolfo et al. (2024) documented the encounter of three YOY in the Gulf of Lion. However, only one of these individuals, which was found near the coast and in a relatively shallow area, was compatible in body length with a newborn (the date of the observation was not provided).

This high use of the NW Mediterranean Sea by most of the satellite-tagged blue sharks during the potential breeding season (Poisson et al. 2024) coincides with the recent findings on the genetic differentiation and phylogeography of this shark, showing a clear genetic separation between the Mediterranean population and those in the Atlantic beyond the Strait of Gibraltar, as well as between the eastern and western Mediterranean basins (Dolfo et al. 2024, Leone et al. 2024). This finding is further supported by the observed long-range movement patterns that seem to be limited within each of the Mediterranean basins and also by the genetic differentiation assessments that show a high genetic homogeneity, which is consistent with panmixia occurring within each of these basins (Dolfo et al. 2024, Leone et al. 2024).

The delimitation of blue shark breeding areas, particularly within the Mediterranean Sea, should be a conservation priority given the species' current classification as critically endangered by the IUCN in this region (Sims et al. 2016), and especially considering that blue sharks show high fidelity to these areas that are used for birthing and mating and as a nursery over time (Domingo et al. 2022). These areas may be important because they are assumed to be used by YOY and juveniles in their first weeks and years of life, as well as by subadults, adult females and adult males, which have different habitat needs and can thus occupy different areas (Vandeperre et al. 2014, Fujinami et al. 2021, Druon et al. 2022). This suggests that these important breeding areas must offer conditions and characteristics appropriate for both sexes and for different ages, as well as including the places of mating, parturition and nursery. Therefore, specific research on blue shark habitat use in the Mediterranean basin is required at a finer scale.

Considering that satellite-tagged blue sharks concentrated in the Gulf of Lion and the waters in front of the northern Catalan coast between spring and early summer (Poisson et al. 2024), when reproduction should occur, we hypothesized that in the submarine canyons of Cape of Creus, Lacaze-Duthiers and Begur/La Fonera are a seasonal blue shark aggregation area. Specifically, we predicted that (a) blue shark concentrations would occur between late spring and summer, (b) adults, including pregnant females, would be present during this period, (c) newborn individuals would also be detected, and (d) given that mating and parturition can occur consecutively, the presence of adults and neonates would overlap or, at most, would be briefly spaced in time. If confirmed, these hypotheses would provide multi-year evidence of blue shark breeding activity in this region. Consequently, effective management of this area would be critical for the conservation of this species in the western Mediterranean Sea.

MATERIAL AND METHODS

Study area

The fieldwork was performed off the northern Catalan coast, situated in the northwestern Mediterranean Sea (Fig. 1A). There, the platform narrows to a width of 3 to 20 km. This sector is crossed by the submarine canyons of Cape of Creus (CCC) and Lacaze-Duthiers (CLD), which merge at greater depths. To the south, there are two other large submarine canyons: Begur or La Fonera (CBF) and Blanes (CBS) (Fig. 1B). Although the whole of this area is situated outside of the Gulf of Lion, it is also included within the polygon in which Poisson et al. (2024) found a blue shark concentration in spring and summer and suggested the possibility of blue shark reproduction. In this study, we refer to this entire area as GOLNCC, encompassing the Gulf of Lion and the northern part of the Catalan coast (NCC).

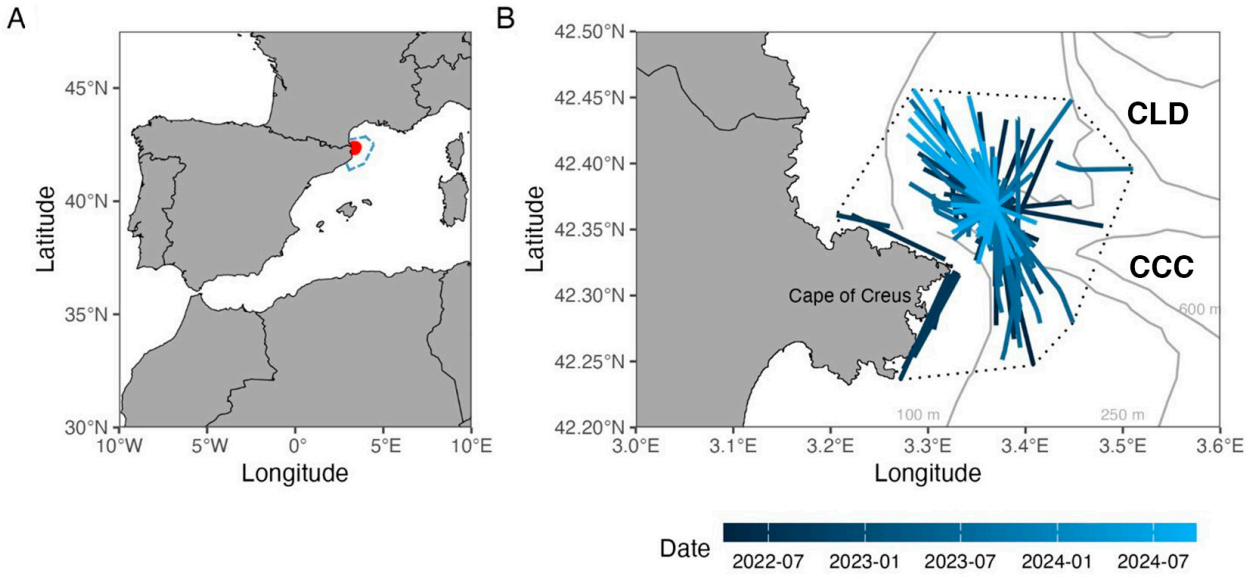

Fig. 1. – A, study area (red square); the area of concentration of tagged sharks in spring and summer found by Poisson et al. (2024) (the minimum area with presence of 50% of the collected fixes), here called the GOLNCC, is marked with a dashed blue line. B, survey tracks (blue lines) and study area (dotted black line). CCC, Cape of Creus canyon; CLD, Lacaze-Duthiers canyon.

The CCC (42°8'N, 3°34'E) is located 5 km northeast of Cape of Creus, off the northeastern tip of the Iberian Peninsula (Fig. 1A). The CCC descends southeastwards, reaching depths of about 1400 m (Madurell et al. 2012). Fieldwork was concentrated in the upper section of the CCC and nearby areas, including part of the CLD (Fig. 1B),

at depths between 0 and 600 m. The seafloor of the CCC and CLD is more rugged and uneven than that of most of the broader GOLNCC and other areas of the western Mediterranean Sea. The region is influenced by prevailing katabatic winds, which descend through the Rhône Valley in a north-south or northwest direction. These winds drive some of the most intense storms in the western Mediterranean, generating waves that can exceed 8 m in height (Fontserè 1950, Facultat de Nàutica de Barcelona 2011). In addition, a permanent marine circulation system has been identified in the area (Font et al. 1988), along with extensive open-sea convection processes (Tamburini et al. 2013). These oceanographic and meteorological conditions contribute to the area's high productivity and exceptional biological richness. As a result, the CCC and its surroundings have been described as a key biodiversity hotspot in the Mediterranean Sea (Domínguez-Carrió et al. 2014).

A second part of the study was conducted along the entire Catalan coast. The continental shelf varies in width along this coast, widening significantly in the south (reaching 40 to 47 km off the Ebro River Delta) and narrowing to just 6 to 10 km in the central section. In adjacent French waters, the continental shelf extends 40 to 70 km before dropping steeply to depths of around 1500 m. This transition occurs along a wide escarpment characterized by a steep slope and highly rugged bathymetry, intersected by numerous small submarine canyons.

Data research

A review of the scientific literature, media sources and grey literature was conducted to compile all known records of blue sharks reported or found along the Catalan coast between 2000 and 2024. Furthermore, we incorporated data from three coordinated monitoring schemes that document shark sightings or strandings (alive or dead) within 100 m of the Catalan coastline: (a) the Registry of the Marine Wildlife Rescue Network (XRFM), Generalitat de Catalunya (Government of Catalonia); (b) the Register of communications to the Corps of Rural Agents (also Generalitat de Catalunya), maintained by the same government body, which is equipped with continuous radio monitoring, is open to external calls, and has the character of a public register; and (c) the database of the Marine Animal Recovery Centre (CRAM) managed by this private non-profit organization. Since the number of blue shark strandings and nearshore encounters per year is relatively small and such events generate a lot of media and social media attention, the probability of cases going unnoticed was considered minimal. To ensure data reliability, only confirmed blue shark records were included. Care was taken to exclude potential misidentifications with other shark species, especially among media-reported cases. Records were accepted only when they were supported by high-quality photographs or videos, confirmed by shark researchers or specialists, or clearly identified in official reports. Duplicate observations, such as simultaneous sightings at nearby locations or on consecutive days, were discarded. For each validated case, the following information was recorded whenever possible: (1) total length (TL) of the shark in metres; (2) age class, based on TL (Table 1), and (3) the geographic coordinates of the encounter.

Table 1. – Correspondence between the total length (TL) and the estimated age class of blue sharks used in this study according to the data of Megalofonou et al. (2009). (YOY) Young of the year (= newborns + older YOY).

Age class	Description	TL (m)	
		Females	Males
NB	Newborn[(1)]	0.35–0.40	
Other YOY	Other young of the year (except NB)	0.41–0.60	
1+	Small juvenile (born the preceding year)	0.60–0.84	
2+	Juvenile 2nd year	0.85–1.24	
3+	Juvenile 3rd year	1.25–1.69	
4+	Subadults	1.70–1.99	1.70–1.89
5+ or older	Adults	≥2.00	≥1.90

Fieldwork

A total of 170 pelagic shark surveys, representing 933 h 6 m (trips not included), were conducted between April and October in 2022, 2023 and 2024. Of these, 161 surveys took place in the CCC, CLD and surrounding areas at depths between 100 and 600 m (894 h 42 m), while nine were conducted near the coastline of Cape of Creus at depths between 30 and 100 m (38 h 24 m). All surveys were conducted during daylight hours, between 07:11 and 17:05 h GMT, with an average duration of 5 h 5 m (sd=2.18; range 3 h 0 m–7 h 6 m). Surveys were distributed across the following months: April (n=8), May (n=23), June (n=43), July (n=50), August (n=25), September (n=10) and October (n=2). Survey effort varied by month, with reduced activity in some periods due to adverse weather and sea conditions.

Sharks were attracted using chum, deployed from a 7.5-m-long rigid inflatable boat, which allowed for a close approach and direct observation of the individuals. The chum we used was as follows:

a) A fish mash composed of European pilchard (*Sardina pilchardus*) was gradually released in small quantities to create a scent trail. The mixture was dispersed both vertically (sinking with added sand) and horizontally (floating). During chumming, the boat drifted aided by a cape anchor, and the engine remained off from the initial location of the boat (42°35'N, 3°4'E).
b) Two sealed and perforated white PVC tubes (62.0 cm in length × 12.0 cm in diameter), each filled with European pilchards, were kept suspended at a depth of approximately 5 m, one off the stern and the one off the bow of the boat.
c) A head or large piece of bait, either Atlantic bluefin tuna (*Thunnus thynnus*) or Atlantic bonito (*Sarda sarda*), was secured to a buoy and rope and deployed into the water as an additional visual and olfactory attractant.

Our objective was to attract sharks to come close, allowing them to approach the boat and circle both suspended bait containers. This facilitated close-range observation for species confirmation, individual identification, sex determination (based on external morphology) and TL estimation.

Once the sharks arrived and the habituation period began, underwater filming and photographs were immediately taken from the boat to ensure documentation in case the sharks left quickly. When the animals became accustomed to the vessel's presence, researchers carefully entered the water to photograph/film them again from a closer distance. Photos and videos were taken using a Canon G7X still camera with a Nauticam NA-G7XMKII waterproof case, along with two GoPro Hero 10 cameras. In 2024, we also used an Olympus Tg6 camera equipped with a device with two parallel lasers separated by 20 cm (Glowdive, model Acho II), which allowed us to measure the shark's length with more precision (Fig. 2).

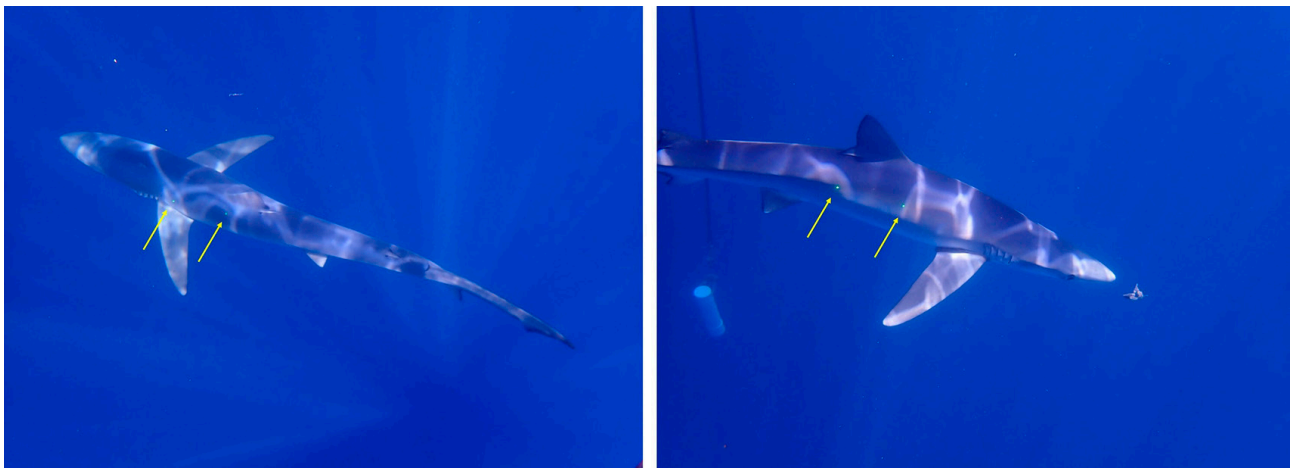

Fig. 2. – Adult female blue shark showing the projection of the light of two parallel lasers on its body (separated 0.20 m) to measure its size (arrows indicate the position of the two points): zenithal view (left) and lateral view (right).

For each encounter, we established (1) the number of different individuals, (2) the coordinates of the first point of observation of each individual, (3) the sex of each individual, (4) the TL (in m), (5) the maximum residence time (*MaxN)* of each individual (Abril et al. 2020), and (6) the presence of wounds, scars, stains, abrasions or other elements that would allow their identification. The sharks were not caught or handled. Sea surface temperature (SST) and underwater visibility were measured in situ during each session.

TL was always estimated by the same observer in two stages: an initial estimation made in situ (to prevent data loss in case of early shark departure), followed by refined measurements from photos and video using the laser system or by comparison with reference objects (e.g. researchers' bodies, vessel elements with known measurements, and equipment such as PVC pipes, buoys, cameras and poles). Water clarity was sufficient for accurate estimations, with a maximum error margin of ±10 cm. For YOY individuals, the error was reduced to ±5 cm. Age classes were assigned based on TL estimates, following classification thresholds established in previous studies (e.g. Megalofonou et al. 2009) (Table 1).

For analytical purposes, individuals estimated to have reached the size associated with sexual maturity were considered adults, although some of them may not have reached maturity yet. While previous studies (Megalofonou et al. 2009, Fujinami et al. 2017, Dolfo et al. 2024) defined maturity using the length at which 50% of the individuals are sexually mature (L_{50}m/f), we chose not to apply those thresholds in our study. This decision was based on two key considerations. First, the cited studies assessed maturity year-round, often outside the breeding season, whereas adult blue sharks in our study area were present during a brief period that likely corresponds to the peak reproduc-

tive season, when a larger proportion of individuals are expected to be mature. Second, we observed potentially mature individuals of smaller sizes than those reported in the literature (e.g. an assumed pregnant female measuring 2.06 m TL). Recent research has shown that shark pregnancy can be identified non-invasively using underwater photo-identification techniques (Jung et al. 2024). In advanced stages of gestation, pregnant females display a characteristic morphology (markedly globular and bulky) that is visually distinct from that of males and from the same females before pregnancy.

We calculated the encounter rate (ER) following Riera-Renter et al. (2024) to standardize blue shark encounters by sampling effort:

$$ER = \text{number of different individuals observed / hour}$$

The ER was calculated for each pelagic survey separately and for each age class: adults, juveniles and YOY.

Statistical analysis

We used a chi-square test to examine the number of sharks per month, with the null hypothesis stating no significant differences between months. We used a Student t-test to compare the means for normal variables (average ER per time period). To assess the seasonality of the blue shark presence in the CCC, we used generalized additive models for each age class (YOY, juvenile and adult), including the ER as the response variable and the yearday (1-365; from 1 January to 31 December) as the predictor variable.

RESULTS

Blue sharks found along the Catalan coast

Between 2000 and 2024, a total of 37 blue shark (*P. glauca*) records were documented along the Catalan coast (Fig. 3; Suplementary Material Table S1). Most observations (75.7%) occurred between 15 May and 31 August, showing a statistically significant temporal concentration (χ^2=9.877; df=8; p<0.0017). Two of the records corresponded to YOY individuals (5.4% of the total), both observed in shallow waters (Table 2). The first one was filmed moving a few metres from the coastline of Llafranc (41°53'N, 3°11'E) in August 2023, and the second was observed in the port of Palamós (41°50'N, 3°7'E) on 11 July 2024. Both sightings occurred in the area where the head of the CBF gets closer to the coast. In addition, a small juvenile (age class 1+) was recorded in Portbou (42°26'N, 3°10'E) in July 2022, near the head of the CCC.

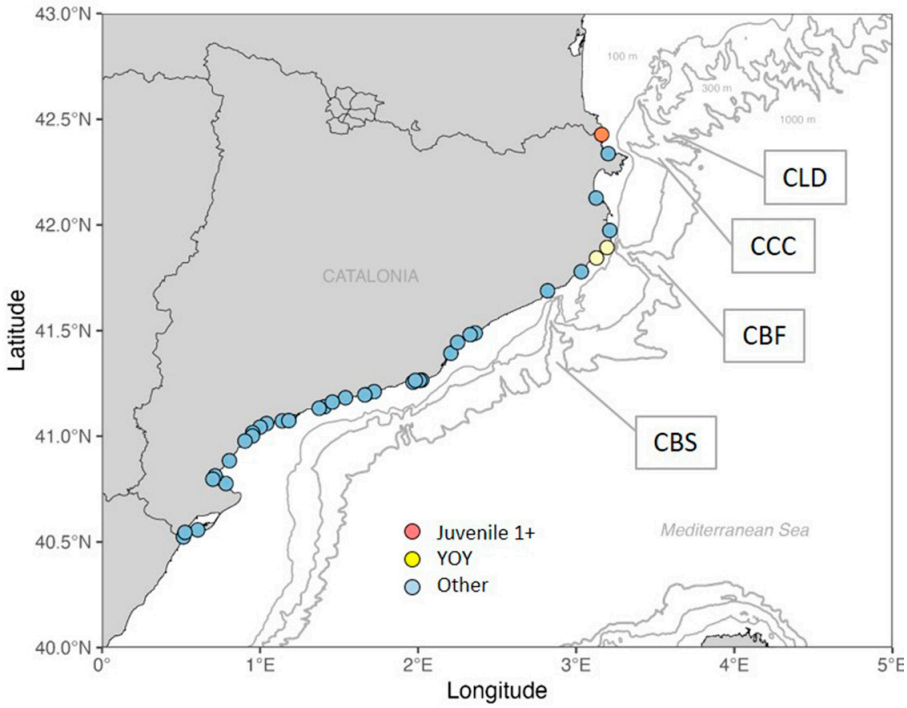

Fig. 3. – Distribution of blue sharks found on the coast of Catalonia between 2000 and 2024 according to age classes. CCC, Cape of Creus canyon; CLD, Lacaze-Duthiers canyon; CBF, Begur or La Fonera canyon; CBS, Blanes canyon; YOY, young of the year.

Table 2. – Blue shark young of the year detected in the study area during the years 2022 and 2023; those that may be newborns according to their small estimated size (TL=0.35–0.40 m) are marked in bold letters and underlined. This is not the case with the two specimens observed in the CBF, which could not be measured with precision. Visibility, estimated via a Secchi disc, was always good enough to easily distinguish the individuals from at least 8 m. Although the residence time of some of the specimens was relatively short, all showed a very confident behaviour and could be observed and measured with elements of known dimensions at a very short distance, usually 0.5–1.0 m. CBF, canyon of Begur or La Fonera; CCC, canyon of Cape of Creus; *MaxN*, maximum residence time; TL, estimated total length.

ID	Date	TL (m)	Detection Time (GMT) (hh:mm)	*MaxN* (hh:mm)	Seafloor depth (m)	Wind (kts)	Visibility (m)	SST (°C)
CCC-1	19/06/2022	0.35	10.30	00:03	128	8.10	13.0	22.9
CCC-2	29/06/2022	0.35	11:02	00:08	129	4.86	16.0	23.7
CCC-3	29/06/2022	0.40	12:05	00:02	131	4.86	16.0	23.7
CCC-4	05/08/2022	0.40	14:38	00:10	240	2.16	25.0	27.0
CCC-5	24/06/2023	0.35	13:49	00:02	123	6.75	12.0	24.0
CCC-6	25/06/2023	0.35	14:10	00:05	308	9.25	9.0	25.5
CCC-7	27/06/2023	0.35	10:44	00:11	115	19.85	8.0	24.35
CCC-8	27/06/2023	0.50	12:50	00:05	110	19.85	8.0	24.35
CCC-9	14/07/2023	0.40	11.35	00:03	158	8.85	12.0	24.3
CCC-10	26/07/2023	0.50	15:47	00:23	276	16.95	19.0	23.5
CBF-1	26/08/2023	0.35–0.60	Morning	00:03	0.2	-		23.8
CBF-2	27/06/2024	0.35–0.60	Morning	-	3.0	-		-

Fieldwork in the CCC and CLD

No blue sharks were observed during the nine surveys conducted in the shallower nearshore areas. Therefore, the following analyses focused on the 161 surveys carried out in the CCC, CLD and surrounding zones. A total of 213 blue shark observations were recorded between 26 April and 28 September over the three study years. The different body sizes, sexes, presence of hooks and/or nylons, scars, injuries, marks and signs recorded demonstrated that only one shark was observed twice (considering data from each year separately).

The mean SST during the study period was 22.3°C (sd=5.97), ranging from 12.4°C in April to 27.1°C in August. Average water visibility, measured with a Secchi disc (from June 2022 to September 2024), was 16.01 m (range: 8–29 m). Some 2022 surveys in which visibility was estimated visually from underwater were exclude.

The mean ER (mean±sd) during the period when sharks were present (24 April – 28 September) was 0.27±0.08 individuals per hour (n=154 surveys). Between 11 June and 31 July of the three study years, which corresponded with the period with higher presence of adults and YOY, the mean ER increased to 0.42±0.44 (n=81 surveys). In contrast, during periods outside this window, when only juveniles were observed (i.e. before 3 June and after 5 August), the ER dropped significantly to 0.14±0.18 (n=71), and the differences were significant ($t=-4.5$; $p<0.0001$)

YOYs and potential breeding adults in the CCC and CLD

Of 208 individuals with assigned age class, 162 were juveniles and 14 were subadults, representing 83.6% of observations as a whole. Adults (age ≥5) made up 12.0% (n=25), comprising 21 males and 4 females. The mean TL of adult males was 2.11 m (sd=9.8 cm; range 2.00–2.30 m), while females averaged 2.30 m (sd=23.1 cm; range 2.06–2.50 m). Ten YOY individuals (age class 0+) were recorded during the surveys in the CCC and CLD: four in 2022 and six in 2023 (Table 2; Fig. 4). YOY represented 4.4% of all aged individuals.

Characteristics of YOYs

Including the two YOY individuals observed near the CBF, 12 YOY were recorded in total. Their estimated TL ranged from 0.35 to 0.60 m (Table 2), and they were observed during daylight hours between 08:30 and 16:10 GMT. The average SST at the time of detection in the CCC was 24.3°C (sd=1.11; range 22.9–27.0°C). The seafloor depth at the point of observation ranged from 0.2 to 308.0 m.

Of the YOY, 83.3% had an estimated TL of ≤0.40 m, suggesting they were newborns, likely born within the study area. These small YOY will hereafter be referred to as newborns.

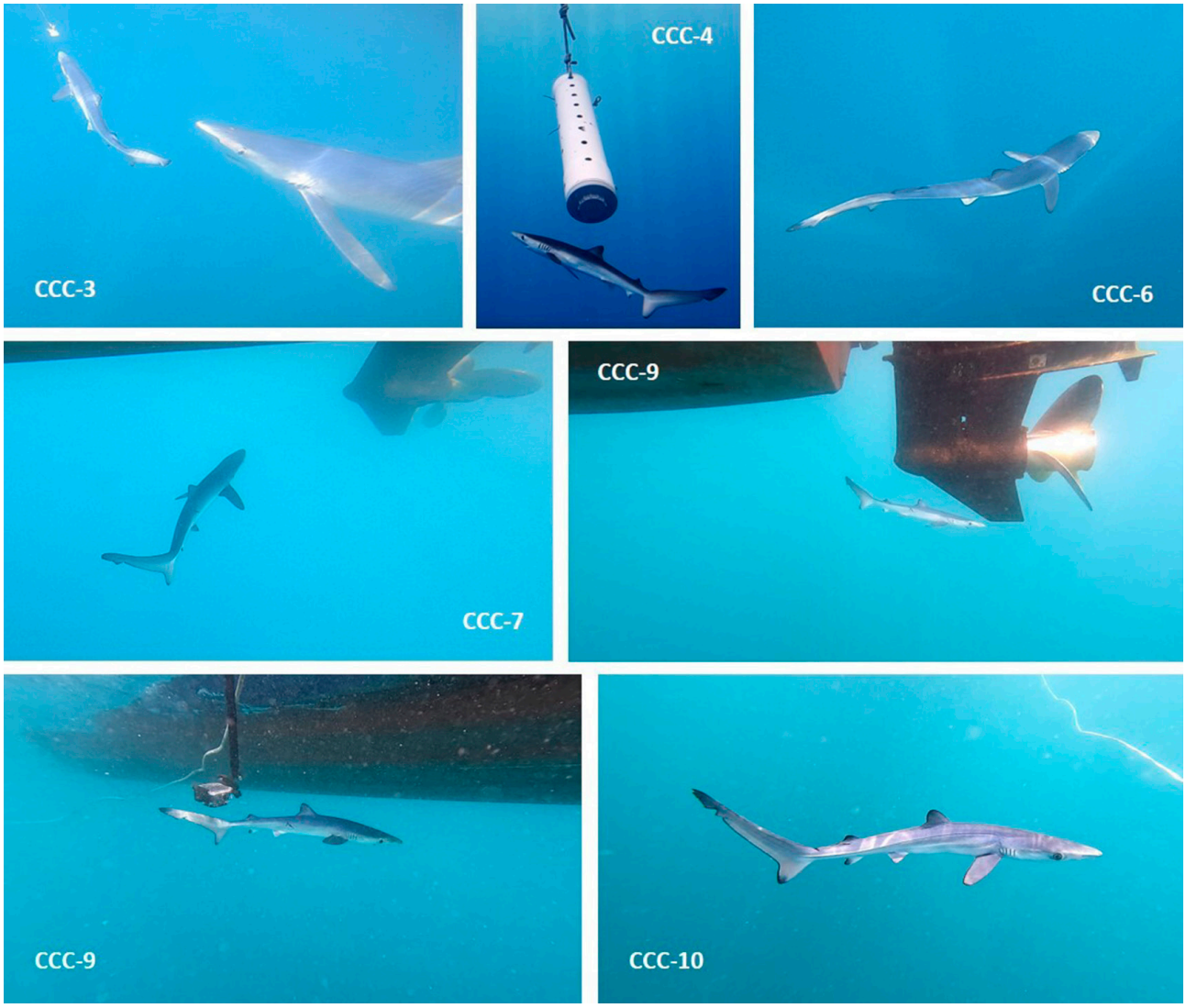

Fig. 4. – Six of the blue shark young of the year found during the present study (ID according to Table 2), all them classified as newborn except CCC-10. CCC-3 is close to a juvenile male of the age class 3+ (TL=1.60 m), as a reference; CCC-9 is compared to a small boat and a GoPro Hero 10 camera.

Seasonality in the CCC and CLD

Two-thirds (66.7%) of YOY sightings occurred between 21 and 30 June, and the figure rose to 90.0% in the broader period between 19 June and 14 July.

All potential reproductive adults (n=25) were observed between 3 June and 31 July, with records from each of the three study years: 2022 (n=3), 2023 (n=14) and 2024 (n=8). The 2.06-m-long female observed in July 2024 was likely pregnant. No adults were recorded in April, May, August or beyond.

We observed a significant seasonal pattern for adults ($F=3.344$; $p=0.0019$) (Fig. 5), with a peak in June. YOY were recorded between 10 June and 20 July, although their seasonality was not statistically significant ($F=1.390$; $p=0.2629$), probably due to low sample size. Adults and newborns were observed simultaneously. In contrast, juvenile sharks exhibited a different and more prolonged seasonal pattern ($F=1.390$; $p=0.0047$) (Fig. 5), with their peak occurring later than that of adults. Subadults were excluded from this analysis due to the limited sample size.

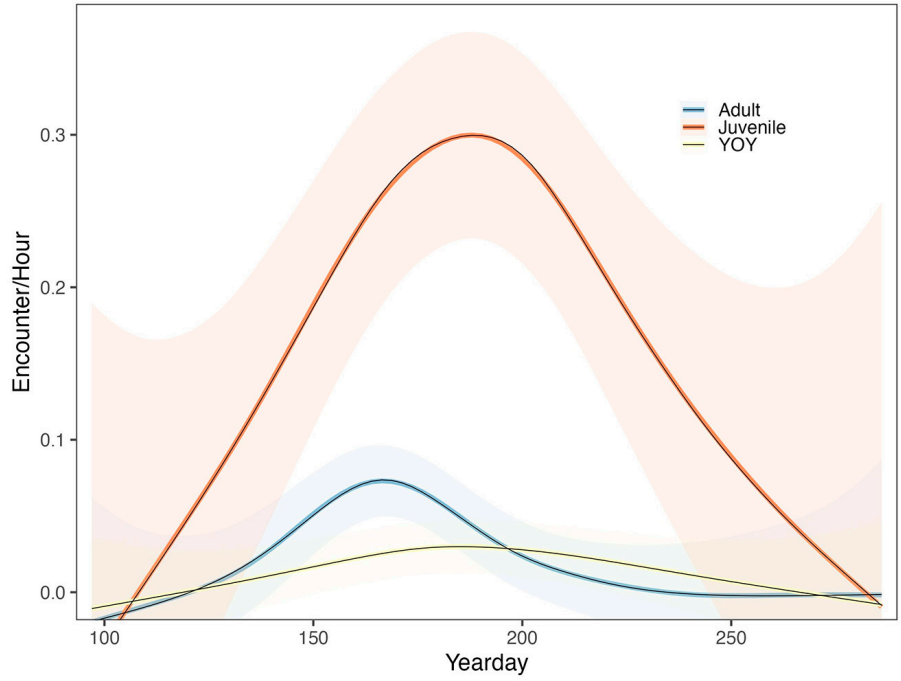

Fig. 5. – Age classes of blue shark encounter rate (individuals encountered/hour) in the Cape of Creus canyon and its surroundings throughout the year (Yearday) established by means of generalized additive models. YOY, young of the year.

DISCUSSION

Temporal concentration of blue sharks in the CCC

According to Poisson et al. (2024), significant seasonal aggregations of blue sharks were found in the CCC and CLD between late spring and summer. Our study supports this finding, revealing a consistent temporal pattern of blue shark presence in this period across all three years of monitoring, thus confirming our first hypothesis. The ER during the period when sharks were present (24 April – 28 September) averaged 0.27 individuals/hour, considerably higher than the 0.02 individuals/hour reported by Abril et al. (2020) in the Balearic Islands. However, this difference may be partially explained by seasonal variability, as our surveys were conducted during the peak presence period (spring-summer), while Abril et al. sampled during a less favourable season. In June and July, the mean ER increased to 0.42 individuals/hour. In contrast, shark encounters were low during the remaining months (April, May, September and October). Although our encounter rates are somewhat low compared with those in other global shark hotspots, they must be considered in the context of the species' steep population decline (Sims et al. 2016) and its current low abundance (Dolfo et al. 2024). Recaptures, defined as individuals observed two or more times per year, were rare. These results confirm that, during early spring and summer, a concentration occurs in the CCC, the CLD and the whole GOLNCC (Poisson et al. 2024). The low number of recaptures in our study may be indicative of a relatively large and mobile population exploiting the GOLNCC.

Juveniles (including subadults) comprised the majority of individuals sighted within the CCC and CLD, highlighting the importance of this area for these life stages. Nonetheless, 12% of the sightings corresponded to adult males and females, and approximately 4% to YOY, indicating that the area is also used, albeit to a lesser extent, by other age classes.

Our results contrast in part with those of Dolfo et al. (2024), who reported no adult blue sharks in the GOLNCC. Poisson et al. (2024) also primarily tagged juveniles. These discrepancies may reflect differences in study areas, as our sampling sites differ in bathymetric and oceanographic characteristics. For instance, most of French waters feature a broader continental shelf situated further from submarine canyons, often in shallower habitats. Such orographic differences may also influence productivity and/or fishing pressure, both of which could affect shark distribution. Temporal mismatches in sampling periods or gear types may also contribute to the variation between studies.

The significant concentration of blue sharks found in the present study and in Poisson et al. (2024) occurs in a highly productive area and coincides with the reproductive season of the species. Supporting this, Poisson et al. (2024) also observed some females with fresh biting marks that had likely been inflicted by males during copulation. Additionally, they stated that professional fishermen have also recorded newborn blue sharks in the area during spring and summer, and Dolfo et al. (2024) collected some YOY blue sharks in the Gulf of Lion.

Breeding of blue sharks in the CCC, CLD and CBF

This study provides the first clear evidence of blue shark breeding in the CCC, CLD and CBF areas. We recorded 12 YOY individuals, whose small size and reduced swimming capacity suggest that they were born a few days before in a nearby area. In addition, several adults were observed during June and July, including a female that was likely in an advanced state of gestation. These findings confirm our second and third hypotheses. A previous observation of a pregnant female along the Valencian coast in September (Penadés-Suay et al. 2017), with embryos in the early stages of development, supports this pattern. It is plausible that such individuals migrate towards southern areas and temporarily inhabit the submarine canyons of the GOLNCC.

Globally, knowledge of blue shark mating, birthing, and nursery grounds remains limited (Domingo et al. 2022). Blue shark females select birth areas to ensure the survival of newborns (Nakano and Stevens 2008, Vandeperre et al. 2014, Coelho et al. 2017). Those selected birth and nursery areas tend to be in relatively cold and highly productive waters, coinciding with late spring and the first half of summer in temperate regions, conditions that align well with those observed in the CCC, CLD and CBF. The combination of environmental suitability and reproductive importance may also explain the high fidelity of blue sharks to these areas over time (Pratt and Carrier 2001). Notably, both adults and YOY individuals were observed during all three years of the study, reinforcing the potential significance of these areas for blue shark reproduction. Given that these areas offer particular resources that enhance the breeding success and fitness of blue sharks, there is a high fidelity to them over time (Pratt and Carrier 2001).

In the Mediterranean Sea, information on blue shark reproduction is even scarcer than in other parts of the world. In the eastern basin, the presence of YOY has led to the identification of potential breeding areas in the Adriatic and Ionian Seas (Megalofonou et al. 2009, Ćetković et al. 2019), while another likely breeding ground has been identified between Corsica, Sardinia and Tuscany (Mancusi et al. 2023). Our findings complement recent studies by Poisson et al. (2024) and Dolfo et al. (2024), confirming the existence of an additional breeding ground in a relatively small area of the northwestern Mediterranean.

Patterns of blue shark movement and migration are closely linked to (a) reproductive behaviour, (b) spatiotemporal variation in prey availability and (c) physicochemical oceanographic conditions (Bigelow et al. 1999). Poisson et al. (2024) highlighted that the GOLNCC has the coldest waters of the western Mediterranean throughout the year, especially at the end of spring and summer, combined with high primary productivity driven by the enormous discharge of water and nutrients produced by the river Rhône. The region also hosts an anticyclonic eddy, shaped by prevailing sea currents and northerly winds, which further enhances local productivity. Additionally, the seabed in the GOLNCC is characterized by complex topography, including steep slopes, rough textures and numerous submarine canyons. All these characteristics may help explain the blue shark concentration found in this area and the habitat suitability for potential reproduction of this species.

Seasonality and temporal overlap between adults and newborns

Adult blue sharks exhibited a clear seasonal pattern throughout the study period, with most individuals being observed between 1 June and 10 July. Although the seasonal pattern for YOY individuals was not statistically significant due to the small sample, they were primarily observed between mid-June and mid-July. This temporal overlap with adults supports our fourth hypothesis regarding the synchrony between mating and parturition periods.

Most YOY were recorded within a narrow time window, between 18 and 30 June, when individuals also showed the smallest total lengths. This pattern suggests a simultaneous onset of births, aligning with the summer solstice. While our current sample size limits precision, we expect that a larger dataset would allow a more accurate delineation of the birthing period.

From late June onwards, sightings of newborns became increasingly infrequent, and after 5 August no further YOY were observed. This suggests a gradual departure from the canyon area, likely in search of new habitats, as has been reported in other regions (Bañón et al. 2016, Mancusi et al. 2023). Notably, the two newborns observed in the CBF were located near the head of the canyon but outside of it, in very shallow waters, which aligns with previous findings of their habitat selection.

Our results point to a concentrated mating period occurring mainly in June and early July, with the majority of births taking place during the second half of June. These breeding periods align with those documented in other regions of the species' distribution. Furthermore, the apparent synchrony observed between mating and birthing is consistent with known reproductive physiology in blue sharks, where females ovulate, mate and begin gestation immediately after giving birth (Domingo et al. 2022).

The need for management or protection of this blue shark breeding area

The GOLNCC, including the CCC, the CLD and the CBF, seems to act as an important area for the conservation of the blue shark in the western Mediterranean Sea. Evidence indicates that it is likely the main breeding ground supporting mating, parturition and early phases of nursery. Furthermore, it plays an important role in the growth

and survival of juveniles. These three submarine canyons—and likely adjacent sectors—are characterized by cold, productive waters and a rugged, deep seafloor, which together may create ideal conditions for blue shark reproductive activities and early development. Given its ecological significance, the GOLNCC is not only critical for blue sharks but also for other endangered large pelagic shark species that have been observed in recent years, including the common thresher (*Alopias vulpinus*), the shortfin mako (*Isurus oxyrinchus*) and the basking shark (*Cetorhinus maximus*) (Carpaye-Taïlamée 2019, Nuez et al. 2021). Protecting and/or managing this area would therefore benefit a wider community of vulnerable pelagic species.

Numerous studies recommend implementing spatial and temporal management measures—such as restrictions on fishing gear, fishing effort and seasonal closures—in known breeding and nursery habitats to enhance reproductive success (Heupel et al. 2007, Heithaus 2007, Riera-Renter et al. 2024). The GOLNCC, given its ecological continuity across national boundaries, should be managed through a transboundary conservation framework. Sharks are highly mobile and routinely move between territorial waters, emphasizing the need for cooperative international management of this shared habitat.

According to Poisson et al. (2024), the GOLNCC, the minimum area with presence of 50% of blue shark occurrence in June and July, spans approximately 13596 km²— about 1.6% of the total surface area of the western Mediterranean Sea. Protecting and sustainably managing this area could yield substantial conservation benefits for blue sharks and other associated species.

Importantly, the GOLNCC is situated within a region recognized for its unique oceanographic features and exceptional biodiversity, making it one of the most important ecological hotspots in the Mediterranean (Domínguez-Carrió et al. 2014). Despite this, the GOLNCC has been only partially recognized in the current classification of Important Shark and Ray Areas (ISRA) in the Mediterranean (Jabado et al. 2023). Given our observations of blue sharks, basking sharks and other large pelagic predators within this area, we strongly recommend a revision of this classification. The GOLNCC should be fully included within the ISRA framework to ensure its protection and to reflect its critical role in the life cycles of multiple vulnerable shark species.

SUPPLEMENTARY MATERIAL

The following supplementary material is available through the online version of this article:

Table S1. Blue sharks found on the Catalan coast between 2000 and 2024. TL, total length; YOY, young of the year.

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AUTHORS' CONTRIBUTION STATEMENT

Jordi Ruiz-Olmo: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. **Clara E Calatayud Pavía:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review and editing. **Isabel González Lobato:** Data curation, Investigation, Resources, Methodology, Validation, Visualization, Writing – review and editing. **Carla Valdés Galiana:** Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – review and editing. **Marc Ruiz-Sagalés:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. **Jordi Riera-Renter:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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