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Resilience in the line: insights on post-release survival from long-term monitoring and satellite tagging of blue sharks (*Prionace glauca*) in the Southern Adriatic Sea

Pierluigi Carbonara [a], Andrea Bellodi [b,c,*], Giulia Prato [d], Simone Niedermüller [e], Alessandro Buzzi [e], Cosmidano Neglia [a], Lola Toomey [a], Massimiliano Bottaro [f], Maria Cristina Follesa [c], Walter Zupa [a]

[a] Fondazione COISPA ETS, Via dei Trulli 18/20, 70126, Bari, Italy
[b] Department of Life and Environmental Sciences, University of Cagliari, via T. Fiorelli 1, 09126, Cagliari, Italy
[c] Department of Integrated Marine Ecology, Calabria Marine Center, Stazione Zoologica Anton Dohrn (SZN), C.da Torre Spaccata, Località Torre Spaccata, 87071, Amendolara, Italy
[d] WWF-Italia, Via Po 25/c, 00198, Rome, Italy
[e] WWF-Mediterranean, Via Po 25/c, 00198, Rome, Italy
[f] Department of Integrative Marine Ecology, Genoa Marine Centre, Stazione Zoologica Anton Dohrn - Italian National Institute of Marine Biology, Ecology and Biotechnology, Villa del Principe, Piazza del Principe 4, 16126, Genoa, Italy

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ABSTRACT

The bycatch of pelagic sharks in Mediterranean longline fisheries remains a critical conservation issue with potential cascading effects on pelagic ecosystems. This study is the first to provide an integrated assessment of blue shark (*Prionace glauca*) bycatch and post-release survival in the southern Adriatic Sea, combining multi-year fishery monitoring, fisher cooperation, and satellite telemetry. From 2019 to 2024, data were collected through on-board observation, landing-site monitoring, and fisher logbooks, ensuring representative spatial and temporal coverage of the swordfish longline fleet. Catch rates remained stable, but landings declined after 2021, suggesting greater compliance with no-retention measures and increased awareness among fishers.

A total of 45 blue sharks were equipped with pop-up satellite tags, which yielded an estimated post-release survival rate of 77%. The majority of mortalities occurred within the first four days. Survival was strongly influenced by capture condition and body size, indicating the higher resilience of adult individuals. A Random Forest model identified soak time as the main determinant of capture condition, followed by environmental variables such as sea-surface temperature, chlorophyll-a, and dissolved oxygen.

Integrating capture-condition frequencies with telemetry data enabled us to estimate that approximately 68% of incidentally captured sharks could survive if released promptly. These findings underscore the ecological importance of reducing blue shark mortality in the Mediterranean, where the species, classified as Critically Endangered, plays a key role as an apex mesopredator. The study demonstrates that empirically guided catch-and-release, supported by fisher cooperation and adaptive management, can enhance ecological resilience and stakeholder engagement in pelagic ecosystems.

1. Introduction

Although there are no large-scale commercial fisheries targeting sharks in the Mediterranean, overfishing is the main cause of decline and local extinctions of sharks and rays in the Mediterranean (Dulvy et al., 2016). Most species are caught as bycatch in small-scale and coastal fisheries, as well as in large-scale trawl and longline fisheries (both pelagic and bottom longline).

Bycatch is the part of the catch that is unintentionally captured during a fishing operation, in addition to the target species. This may refer to the capture of other commercial species that are landed, commercial species that cannot be landed (e.g. undersized or damaged

* Corresponding author at: Department of Life and Environmental Sciences, University of Cagliari, via T. Fiorelli 1, 09126, Cagliari, Italy.
E-mail address: abellodi@unica.it (A. Bellodi).

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individuals), non-commercial species, or incidental catches of endangered, vulnerable or rare species (e.g. sea turtles, sharks, marine mammals) (FAO, 2016) and for this reason bycatch ranks among the most pressing global fisheries issues (Lewison et al., 2014; Gray and Kennelly, 2018).

Particularly concerning is the incidental capture of endangered, threatened and protected (ETP) species in both commercial and artisanal marine fisheries, amounting to over 20 million specimens annually, including seabirds, mammals, elasmobranchs, and sea turtles (Gray and Kennelly, 2018). The Mediterranean Sea is one of the globally most intensely fished areas, which results in high bycatch of ETP species (Carpentieri et al., 2021).

Among fishing gears, longline fisheries, also impact these species, primarily affecting pelagic sharks and rays (pelagic longline), as well as benthic species (bottom longline). Pelagic sharks are retained as bycatch in longline fisheries targeting swordfish and/or tuna. The global status of several pelagic shark species has worsened, including the great white shark (*Carcharodon carcharias*), the blue shark (*Prionace glauca*), and the smooth hammerhead shark (*Sphyrna zygaena*) (Dulvy et al., 2016). At least 15 shark and ray species are reported to have been caught by surface longlines in the Mediterranean (FAO, 2016). Shark and ray bycatch represents around 10–15% of the analysed biomass of tuna and swordfish longline catches (FAO, 2016). The highest catch rates for these fisheries in the Mediterranean were found in the Alboran Sea (34.3%) and the Adriatic Sea (15.1%). Accordingly, the catch-per-unit effort (CPUE) of elasmobranch species is higher in the Alboran Sea (FAO, 2016) and the Adriatic Sea (Carbonara et al., 2023, 2024) than in other areas. Although the phenomenon of ETP species bycatch is particularly intense in the southern Adriatic, there is no systematic bycatch data collection system or monitoring of bycatch (Carpentieri et al., 2021; Carbonara et al., 2025a).

Among pelagic sharks, the blue shark represents over 70% of the chondrichthyan catch (Bradai et al., 2012; Megalofonou et al., 2005). Blue sharks are highly migratory predators widely distributed throughout the temperate and tropical waters of the world's oceans (Compagno, 1984), representing the most abundant pelagic shark species worldwide (Nakano, 1994; Nakano and Seki, 2003). In particular, the blue shark is the most important species landed in Italian fisheries among pelagic sharks (FAO, 2015). These species can play important roles in marine ecosystems through diverse mechanisms, and the decline of large predatory sharks in both coastal and open-ocean ecosystems may indeed initiate trophic cascades, affecting the overall structure of the community (Stillwell and Kohler, 1982; Ward et al., 2004; Heithaus et al., 2008; Ferretti et al., 2010).

Despite its global abundance, the conservation status of the blue shark in the Mediterranean is of particular concern. The species is currently classified as Critically Endangered in the Mediterranean by the IUCN, whereas the Atlantic population is evaluated as Near Threatened. Recent genetic analyses have also shown that Mediterranean and Atlantic populations are not panmictic (not forming a single randomly mating population), indicating significant genetic differentiation between them (Leone et al., 2024). This highlights the importance of conserving the Mediterranean population as a distinct management unit. Currently, blue shark fisheries in the Mediterranean fall under the management framework of the International Commission for the Conservation of Atlantic Tunas (ICCAT) and associated EU regulation (2017/2017). Blue sharks are not subject to a basin-wide no-retention policy; their management therefore relies mainly on reporting requirements, general provisions requiring the release of incidentally caught individuals when possible, and the prohibition of shark finning.

To curb the decline and encourage stock recovery, management bodies have introduced various management measures, such as time/spatial fishery closures, gear modifications, and deterrents. One of the most widely used conservation and management measures is the no-retention policy, designed to reduce overall fishing mortality by encouraging the release of live animals (Gilman et al., 2016). However, the effectiveness of these regulations depends on the survival of released individuals, for this reason, understanding post-release survival is becoming increasingly important in order to monitor the efficiency of achieving the management objectives of no-retention policies (Campana et al., 2005; Musyl and Gilman, 2018; Francis et al., 2023). Several factors could affect the survival rates of sharks released from pelagic longline fisheries, including the time they spend struggling on the line, the geographic area, the handling methods used to release or remove them from fishing gear, and their species-specific resilience, as some species are more sensitive than others to the stress induced by capture (Ellis et al., 2017; Musyl and Gilman, 2019). While physiological studies have identified the species that are most sensitive to capture stress by quantifying at-vessel mortality rates (Ellis et al., 2017), the effects of handling and release methods on the survival rates of sharks have only recently been explored for commercial longline vessels during typical fishing operations (Musyl and Gilman, 2018; Schaefer et al., 2021).

Despite the blue shark's importance in terms of both landing and conservation, data on catches and landings are still scarce and/or scattered (Hung et al., 2024). Moreover, most existing estimates of post-release survival for pelagic sharks derive from fisheries operating in other ocean basins or under different gear configurations, making it difficult to directly extrapolate their results to Mediterranean swordfish longline fleets. This issue is of particular concern in the Adriatic Sea, which has been recognised as a hotspot for the bycatch of this species (Megalofonou et al., 2005; FAO, 2016). In this context, the present study aims to address the knowledge gap surrounding blue shark bycatch in swordfish pelagic longline (SPL) fisheries by providing fishery-specific information on capture conditions and post-release survival, thereby contributing to the evaluation of management measures based on no-retention policies. Specifically, the study quantifies bycatch characteristics, capture and handling conditions, and estimates post-release survival probabilities of blue sharks caught during typical commercial fishing operations, providing information relevant for evaluating the effectiveness of no-retention management policies in reducing fishing-induced mortality.

2. Materials and methods

2.1. Bycatch monitoring

In the South Adriatic Sea (Geographical Sub-Area GSA 18, sensu GFCM-FAO), the largest fishing port for pelagic longline fisheries targeting swordfish is Monopoli (Fig. 1), where more than 80% of vessels authorised to catch swordfish by PL fisheries in the Adriatic Sea are based. Consistent with approaches developed in the western Atlantic Ocean (Gallagher et al., 2014; Diaz and Serafy, 2005), blue shark bycatch monitoring in SPL fisheries has relied on three data sources: i) on-board observers; ii) landing-site observers; and iii) fisher logbooks. Onboard observers recorded, for each specimen (discarded and/or landed), catch date, total length (TL), sex, and geographical position (Carbonara et al., 2025b), as well as fishing effort variables including number of hooks, set and haul times, and hook size and shape. Data on the target species (swordfish) were also collected, including the number of specimens and their size (Lower Jaw-Fork Length, LJFL in cm). Meanwhile, through the presence of observer at port sites, data was collected on the number and size of blue sharks and the number of swordfish landed, together with the number of hooks, the time taken to set the gear at sea and recover it, and the position of the hauls were also collected. Finally, the logbooks compiled by the fishers provided data on the number of specimens landed per haul, together with technical data such as the number of hooks, the geographical position, and the times of landing and hauling, also per haul. On-board observer data provide detailed and standardised records of fishing operations and were used to estimate catch-based metrics, including CPUE and bycatch rates. In contrast, logbook and landing observation data, which provide broader fleet coverage, were used to estimate bycatch proportions in landings.

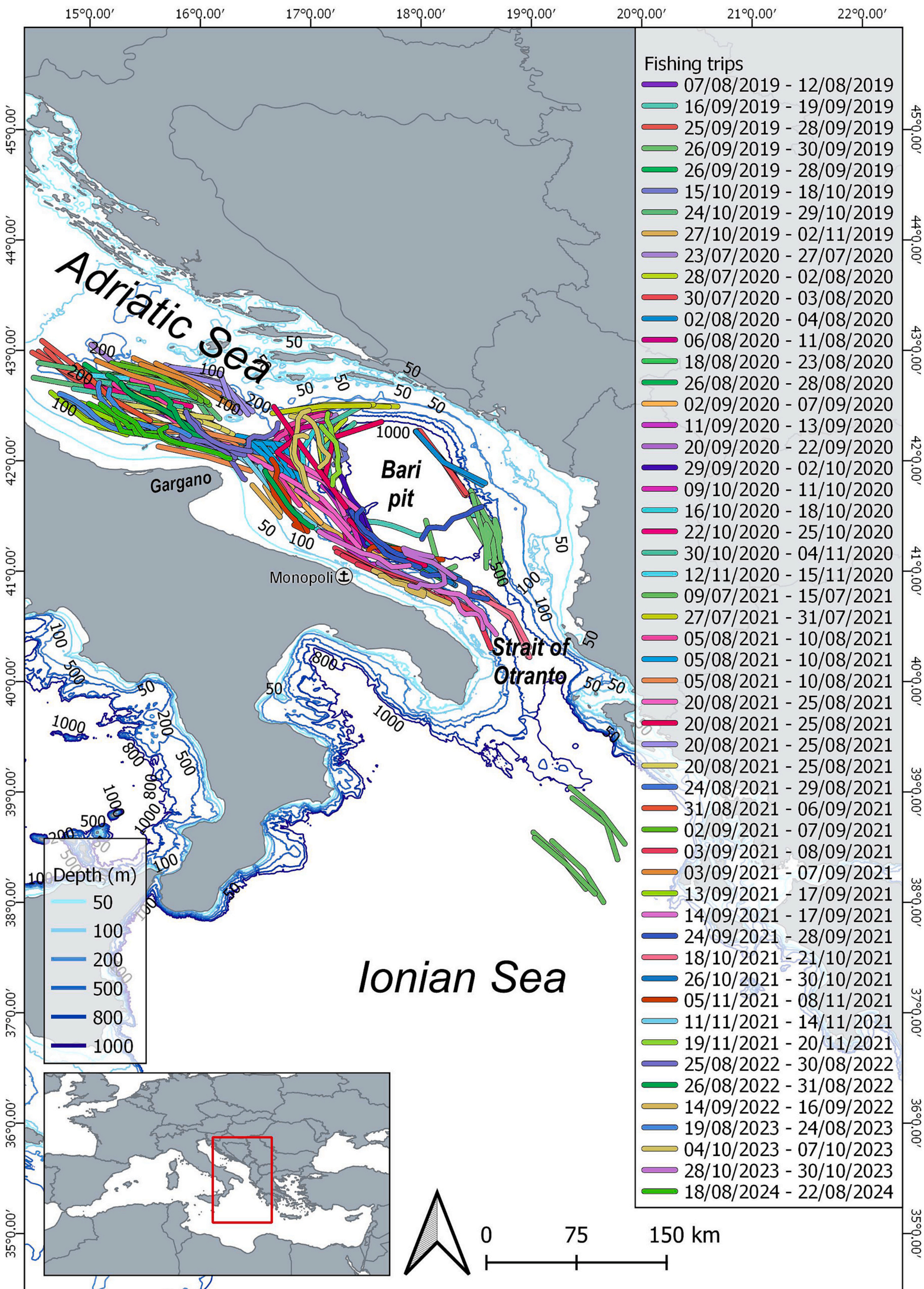

Fig. 1. Spatial distribution of the monitored fishing days (2019–2024). Each line represents a haul and the different colours correspond to the fishing trips.

The total length of the mainline ranged between 30 and 40 km. A hook was attached to a dropline measuring approximately 13 m, with each dropline attached to the mainline at intervals of about 58 m (Carbonara et al., 2023, 2024). The hooks used during the fishing season were J-type hooks (76 mm) settled at a depth of about 30 m from the surface. The longline was set in the early afternoon (3–4 pm), with the operation taking about three hours to complete. Hauling the longline back began at night and finished in the morning at around 7–8 am. The longline hauling started with the last hooks. Therefore, hooks remained in the water for between 10 and 20 h (soak time), defined as the time between the retrieval of a hook group and the end of hauling, representing an operational proxy of exposure time. The baits used during the fishing hauls were frozen mackerel (Scombridae) and plastic squid filled with sardines. An artificial light was attached to the middle of each dropline.

Catch rates were expressed as CPUE, calculated as the number of blue sharks caught per 1000 hooks (Pacheco et al., 2011). CPUE was estimated at the level of individual fishing sets, each corresponding to a fishing day (FD). Annual bycatch rates were calculated as the total number of blue sharks caught divided by the number of fishing days monitored in each year (FAO, 2016). The bycatch percentage landed was calculated by dividing the number of blue sharks landed by the total number of fish landed (target and bycatch) and multiplying the result by 100. The CPUE and bycatch percentage values were compared across years using a Kruskal–Wallis test.

2.2. Tagging and survival

In the context of several projects ("SafeShark" - WWF, 2022; "Med-ByCatch" https://medasset.org/portfolio-item/medbycatch-project/; "Securing healthy populations of Large Pelagics in the Mediterranean sea", https://www.fpa2.org/en/projects/conserving-healthy-populations-of-large-pelagic-fish-in-the-mediterranean-sea-00586), a total of 45 blue sharks were tagged with pop-up satellite archival tags (Wildlife Computers™ pop-up tag) during the monitoring of 13 pelagic longline fishing trips (47 fishing days) targeting swordfish in the southern Adriatic Sea (2019–2024). Two types of pop-up tags were used in this experiment: survivorship tags (sPAT) and archival tags (miniPAT). Each was deployed with a pre-set release time (D-time) of one month for the sPAT and up to one year for the miniPAT. Depth (resolution of 0.5 m) and ambient temperature (resolution of 0.05 °C) data were recorded at 10-min intervals by the sPATs during the final five days of the D-time, and by the miniPATs throughout the entire D-time.

The capture condition of each caught specimen was evaluated during observation on board using a qualitative index system adapted from Benoît et al. (2010), whereby moribund and dead specimens were categorised as a single capture condition (Dapp et al., 2016). The three-stage scale included the following categories: stage 1 = healthy (vigorous body movements), stage 2 = sluggish (weak body movements, responds to touching and prodding), and stage 3 = moribund or dead (no body movements, no response to touching or prodding, movements of the operculum/gill slits noted for moribund individuals or no

Fig. 2. Blue sharks tagging and releasing procedures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

movements of the operculum/gill slits noted for dead individuals). Specimens with capture conditions 1 and 2 were tagged and survival curves as a function of time were estimated by capture condition. All information relating to the individuals who were tagged is available in Supplementary Table 1.

Upon retrieval, hooked sharks were subjected to a tagging procedure (Carbonara et al., 2024). The sharks were blindfolded with a cool, wet cotton cloth, and a tube was inserted into their mouths (Fig. 2). Seawater was gently pumped through the tube to simulate normal swimming behaviour and maintain adequate oxygen flow over the gills (Poisson et al., 2012). The blindfold had a slight sedative effect, keeping the shark calm (Bruce and Bradford, 2013). Immediately before inserting the tag, the shark was gently rolled into left or right lateral recumbency, ensuring a cataleptic state for ease of access and tagging (Otway, 2020). These calming measures are considered to be crucial for human safety, as well as minimising the stress experienced by the captured sharks, and facilitated a controlled tagging environment (Otway, 2020). The tags were attached to the exposed side, close to the first dorsal fin. Tags were attached using a dart-and-tether system. The tag was connected via a monofilament/nylon tether to a stainless-steel dart (anchor). The dart was inserted into the epaxial musculature at the base of the first dorsal fin using a stainless-steel applicator. To facilitate insertion, a small (~2 cm) incision was made through the skin and underlying tissue prior to deploying the dart with its specific applicator. At the same time, the total length (TL) and sex, identified by the presence of pterygopods, were recorded. To conclude the process, blue sharks were released by supporting their pectoral and caudal fins and gently lowering them over the side of the vessel (AFMA, 2014; Poisson et al., 2012; FAO and ACCOBAMS, 2018) (Fig. 2). The entire procedure, including unhooking, taking measurements, and tagging, took between four and eight minutes. Total lengths of every blue shark caught were compared across years using a Kruskal-Wallis test.

Tags were programmed to detach prematurely if they exceeded a critical depth threshold of 1400 m. Independently of this release mechanism, post-release mortality was inferred when tag records indicated that the shark had remained motionless at the same depth for two consecutive days. By contrast, premature tag detachment was not classified as mortality when the shark was still active prior to detachment and no stationary-depth pattern indicative of death was observed. Thus, early tag release per se was not considered evidence of mortality. The post-release survival rates (PSR) of the tagged sharks were estimated by fitting Kaplan–Meier (K-M) survivorship curves (Campana et al., 2009; Musyl and Gilman, 2018). K-M survivorship tracks the loss of sharks from the tagged population as they die and the fitted function was used to predict the proportion of survivors in the population at any given time. As the sharks that were classified as condition 3 (moribund or dead) could not be practically released with a tag, only sharks in capture condition 1 or 2 were included in the tagging experiment and subsequent survival analysis. Consequently, the Kaplan–Meier estimates represent post-release survival conditional on the release of sharks in viable condition. In the survival analysis, tagged individuals classified as dead on the basis of tag records were treated as mortality events. Individuals known to be alive until the time of premature tag detachment, but for which no subsequent fate could be determined, were treated as right-censored observations in the Kaplan–Meier framework. By contrast, tags that failed to transmit and therefore provided no usable post-release information were excluded from the survival analysis, because no defensible classification as either mortality or survival could be made. The modelling of capture condition (Section 2.3) was instead performed on the full set of observed individuals, independently of tagging.

2.3. *Capture condition modelling*

The analysis aimed to estimate the probability of a blue shark specimen being observed in the highest condition class at capture when captured incidentally by an SPL. This analysis was based on a working dataset of 163 sharks sampled between 2019 and 2024 (June–November).

To stabilise the estimation process in the face of strong class imbalance and to align the endpoint with the operational objective of predicting “good condition” (condition 1), conditions 2 and 3 were aggregated (52 individuals), and a binary response (class “1” versus “2–3”) was modelled. While classes 2 and 3 represent biologically distinct states, their aggregation was necessary due to limited sample size and implies that the model distinguishes sharks in good condition from those in any compromised condition at capture. Consequently, the model does not distinguish between weakly responsive individuals (condition 2) and moribund or dead sharks (condition 3), limiting biological resolution across compromised capture states. A Random Forest (RF) modelling framework was employed to estimate the probability that an individual shark would be classified as condition class 1. This analysis was carried out in the R environment using the ranger package (Wright and Ziegler, 2017), which provides a fast and memory-efficient implementation of the algorithm. The RF approach, originally introduced by Breiman (2001), builds an ensemble of decision trees trained on bootstrap samples of the data and combines their predictions to achieve greater stability and predictive accuracy. This method is particularly suitable for ecological datasets where non-linear relationships, complex interactions, and noisy measurements are expected, as it requires no assumptions about data distribution and is inherently resistant to overfitting (Wright and Ziegler, 2017).

In the present study, the forest comprised 3000 trees, which ensured the convergence and stability of the out-of-bag estimates. Out-of-bag (OOB) estimates are internal validation metrics obtained from the bootstrap sampling procedure used to build each tree: for every tree, a subset of observations is left out of the training sample and can therefore be used as an independent dataset to evaluate model performance. Model hyperparameters were tuned to optimise probabilistic performance rather than simple classification accuracy. Specifically, the number of candidate variables considered at each split, the minimum node size, and the sampling fraction were adjusted to minimise cross-entropy loss (log-loss). When alternative parameter combinations produced similar results, the Brier score was used as an additional criterion to favour models with better-calibrated probability predictions (Brier, 1950). To counteract the imbalance between condition classes, inverse-prevalence class weights were applied to give the minority category proportionally greater influence.

Environmental covariates were included in the model as predictors and assembled as monthly surface fields from Copernicus Marine Service (CMEMS) Mediterranean multiyear reanalysis products, with a spatial resolution of 1/24° (Table 1). Sea-surface temperature (SST) and current velocity were obtained from the physical reanalysis product MEDSEA_MULTIYEAR_PHY_006_004, while chlorophyll-a (CHL) concentration and dissolved oxygen (DO) were extracted from the biogeochemical product MEDSEA_MULTIYEAR_BGC_006_008 (Copernicus Marine Service, 2022, 2024; Escudier et al., 2021; Cossarini et al., 2021). Bathymetric information was derived from the EMODnet Digital Terrain Model (DTM, 2024) (EMODnet Bathymetry Consortium, 2024). Another

Table 1
Descriptive statistics of the predictor variables included in the Random Forest model. For each variable, the sample size (n), mean, standard deviation (SD), minimum, and maximum values observed in the modelling dataset are reported. Variables include chlorophyll-a concentration (CHL), dissolved oxygen (DO), soak time (Soak), and sea-surface temperature (SST).

Variable	n	mean	sd	min	max
CHL(mg m^{-3})	163	0.074	0.02	0.049	0.165
DO(mmol m^{-3})	163	212.312	6.244	205.506	234.341
Soak (hours)	163	15.728	3.965	8.233	25.733
SST (°C)	163	24.912	2.164	17.484	27.43

important operational covariate was soak time (hours), which was calculated as the elapsed time between the recorded catch timestamp for each individual and the end of hauling for the corresponding hook group within the same set. This variable was intended as an individual-level proxy for the duration of exposure prior to retrieval. Because the exact hooking time cannot be directly observed during commercial fishing operations, individuals retrieved within the same hook group shared the same soak-time proxy value, defined as the elapsed time between the retrieval of that hook group and the end of hauling. It is important to note that this measure is necessarily affected by some degree of uncertainty and should be interpreted as an approximation of hooking duration. Nevertheless, it was considered biologically meaningful, as relative differences in exposure time are expected to reflect variation in capture stress experienced by the animal. The inclusion of soak time was motivated by empirical and mechanistic evidence indicating that prolonged hooking duration negatively affects the condition of pelagic sharks, including blue shark, and increases at-vessel or post-release mortality (Campana et al., 2009; Hutchinson et al., 2021; Massey et al., 2022). The geographic positions reported in the database were expressed in the WGS-84 coordinate system, and timestamps were harmonised to Coordinated Universal Time (UTC).

Model evaluation was conducted using five-fold stratified cross-validation, whereby the dataset was randomly divided while preserving the original class proportions. This design yields an unbiased estimate of out-of-sample performance and provides a natural measure of variability across resamples. To reduce skewness and improve predictive stability, a logarithmic transformation was applied to the chlorophyll-a and soak time predictors a priori.

Model performance was summarised primarily by the area under the precision–recall curve (PR-AUC), which is the most informative discrimination metric under class imbalance (Saito and Rehmsmeier, 2015). Probability calibration was assessed using cross-entropy (log-loss) as the main optimisation and reporting criterion; the Brier score was used only as a secondary check on overall probabilistic accuracy (Brier, 1950). Metrics dependent on an arbitrary probability threshold or known to be less diagnostic under imbalance were not used to inform interpretation.

To facilitate interpretation, the contribution of the covariates was examined using permutation importance, quantifying the decrease in predictive accuracy when a variable is randomly perturbed. This was followed by partial-dependence profiles for the most influential predictors. The latter provides marginal response shapes for P(condition = 1), thereby revealing non-linearities and interaction footprints (Friedman, 2001).

The main limitations of this analysis stem from the modest sample size and the low representation of condition categories 2 and 3 when further aggregated. Despite these limitations, the chosen non-parametric approach was deemed appropriate for small, heterogeneous datasets and enabled robust estimation of class probabilities.

3. Results

3.1. Bycatch monitoring

The monitoring activities carried out between 2019 and 2024 are reported in Table 2. In total, 66 fishing trips (18 onboard trips, 39 logbook and 9 at landing) and 248 fishing days (66 onboard trips, 151 logbook and 33 at landing) were monitored over six years. In a pre-survey (Safeshark project; WWF, 2022), information was collected on the seasonality, the technical characteristics of the gear, the fishing area, and the species landed. Swordfish fishing in the Southern Adriatic Sea starts in May and finishes at the end of October/beginning of November. During the first two months (May–June) of the swordfish fishing season, a mid-water longline is usually used, whereas a surface longline is used for the rest of the season. In the former case, the depth reached by the longline is around 500 m, whereas the surface longline reaches a shallower depth of 50–60 m (Cambiè et al., 2010). The capture of blue sharks, in particular, and sharks in general, appeared negligible in the swordfish mid-water longline.

Of the total 248 FD monitored, we collected location data for 83.5% (207 FD; Fig. 1). The main fishing areas were concentrated north of the Gargano and around the Fossa di Bari in the west. Furthermore, some fishing trips extended into the Strait of Otranto and, less frequently, into the north-eastern Ionian Sea.

The percentage of coverage on total fishing days (https://stecf.ec.europa.eu/data-dissemination/fdi_en) carried out in GSA18 per year is reported in Table 3. Coverage ranged from 3.17% in 2024 to 16.54% in 2021.

The results of the CPUE and bycatch rate by year are reported in Fig. 3. There were no significant differences in mean CPUE among the years. The bycatch rate significantly decreased from approximately 3 individuals per fishing day in 2019–2020 to approximately 2 individuals per fishing day in 2021–2024 (Kruskal–Wallis test, $p < 0.05$).

The bycatch percentage by year is reported in Fig. 4. After 2021, there was a significant decrease for the following three years (2022–2024) while the swordfish landings did not show any particular trend in the same period (Fig.S1).

Table 2
Number of fishing trips and fishing days monitored by year, month and monitoring strategy.

		July		August		September		October		November	
	Monitoring strategy	Fishing trips	Fishing day	Fishing trips	Fishing day	Fishing trips	Fishing days	Fishing trips	Fishing days	Fishing trips	Fishing days
2019	On-board	0	0	1	5	1	3	0	0	0	0
	Logbook	0	0	0	0	3	11	3	13	0	0
2020	On-board	0	0	2	10	2	3		2	0	0
	Logbook	2	5	1	5	1	2	2	4	0	3
	Observation at port	1	5	1	2	1	5	2	4	1	3
2021	On-board	0	0	1	5	2	4	1	3	1	3
	Logbook	2	9	6	30	3	14	1	4	1	3
	At landing	0	0	1	5	2	9	0	0	0	0
2022	On-board	0	0	2	10	1	2	0	0	0	0
	Logbook	0	0	2	10	3	9	0	0	0	0
2023	On-board	0	0	1	5	0	0	2	5	0	0
	Logbook	2	7	2	7	0	0	2	6	0	0
2024	On-board	0	0	1	4	0	0	0	0	0	0
	Logbook	0	0	1	3	3	10	0	0	0	0
TOTAL		7	26	22	101	21	68	13	41	3	12

Table 3
Coverage of the Fishing days monitored by year, including the total number of fishing days (FD) in the area; the total number of monitored FD, along with the coverage percentage. The number of FD monitored by each method (Observer on board OB; Observers at landing port LP, and Logbook LB) is also reported.

Year	Total FD in GSA18	FD monitored	Coverage percentage (%)	FD by monitoring strategy		
				OB	LP	LB
2019	691	32	4.63	8		24
2020	561	53	9.45	15	19	19
2021	538	89	16.54	15	14	60
2022	666	31	4.65	12		19
2023	341	30	8.81	10		20
2024	536	17	3.17	4		13

3.2. Tagging and survival

A total of 45 blue sharks (23 females and 22 males) were tagged, with TL ranging from 97.5 to 224 cm (Table S1). The majority of the specimens had TLs between 130 and 200 cm (Fig. 5).

The locations where the tagged specimens and tags were released are reported in Fig. 6. For sPATs, lasting up to a month, the tag almost always detached from the blue shark in the Adriatic Sea, while for miniPATs, this occurred far from the release point (Fig. 6).

Of the 45 tagged blue sharks, six tags did not transmit, and it was therefore not possible to determine their fate; these individuals were therefore excluded from the survival analysis. Of the remaining 39 blue sharks, nine died within the first four days, while 30 survived. Overall Kaplan–Meier estimated survival was 76.9% (95% CI: 64.8–91.4%) (Fig. 7a). The tags remained attached to the tagged animals for periods ranging from 12 to 366 days. Mortality after tagging was concentrated in the first four days after release, with seven of the nine dead tagged specimens dying within the first two days after release. The K-M survival showed no significant differences by sex ($p > 0.05$) (Fig. 7b). Kaplan–Meier survival estimates were 80.0% (95% CI: 65.8–97.3%) for condition 1 and 71.4% (95% CI: 51.3–99.5%) for condition 2. Survival curves did not differ significantly between capture-condition groups (log-rank test: chi-square = 0.3, df = 1, $p = 0.608$) (Fig. 7c).

The mortality was concentrated among specimens that were smaller/younger with TL < 170 cm (Fig. 8). Indeed, of the nine specimens that died after capture, eight had a TL between 97.5 and 168.9 cm.

Considering the condition of the fish at the time of capture, of the 39 specimens with functioning tags, 25 showed condition 1 and 14 displayed condition 2.

During embarkation, fish condition at capture was recorded for 163 blue sharks, of which 68.3% (112 specimens) were in condition 1, 17.8% (29 specimens) in condition 2, and 13.5% (22 specimens) in condition 3. The length-frequency distribution of the blue sharks caught is reported in Fig. 9 and shows that most of the captures were specimens with TL between 140 and 180 cm, which were mainly sub-adult or adult

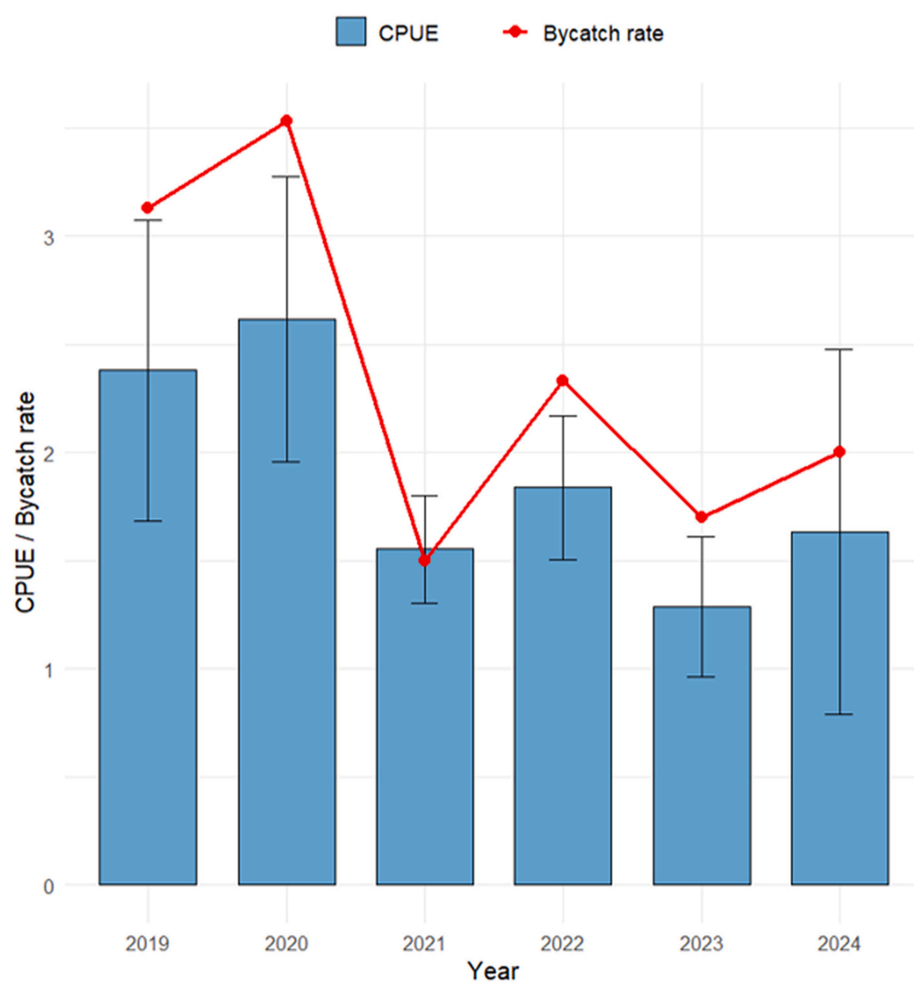

Fig. 3. Average blue shark CPUE by year. The bars represent the standard error. The letters indicate the lack of significant differences in CPUE between years (Kruskal–Wallis $p > 0.05$). The red line shows the bycatch rate by year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

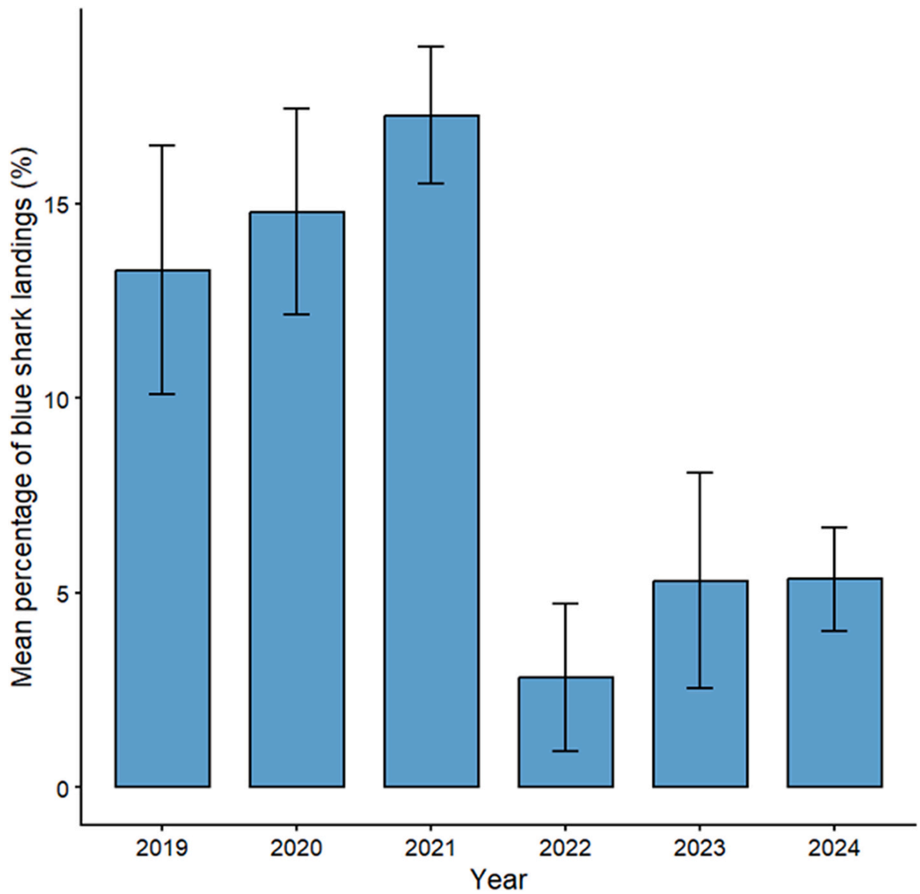

Fig. 4. Mean percentage of blue shark landings by year. The bars represent the standard error. Different letters indicate significant differences (Kruskal–Wallis p > 0.05) in the mean percentage between years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

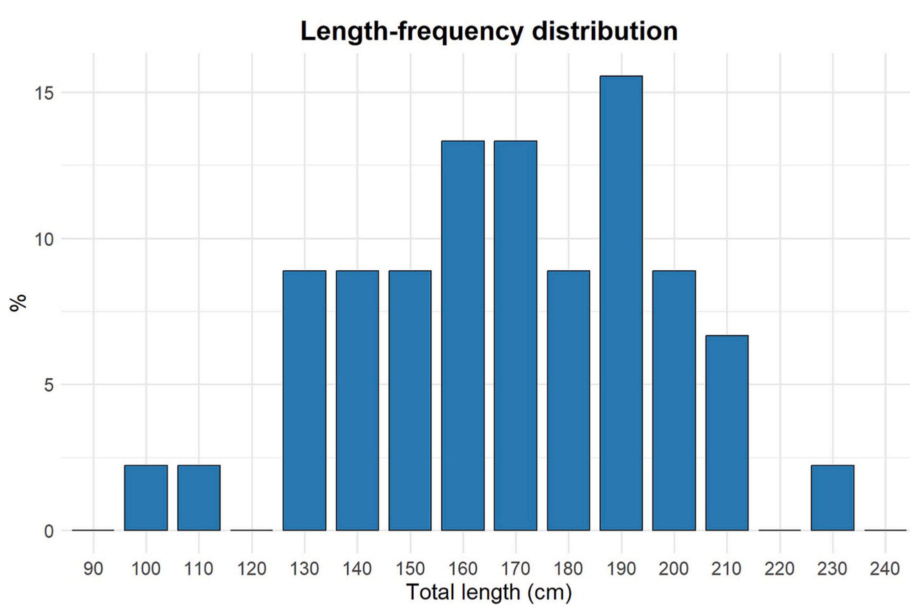

Fig. 5. Length frequency distribution of the blue sharks that were tagged with pop-up satellite tags. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

specimens. The same pattern is evident for both sexes (Fig. 9b).

Analysis of the TL by year revealed no significant differences ($p > 0.05$) in the size of blue sharks captured during the sampling period (2019–2024) (Fig. 10).

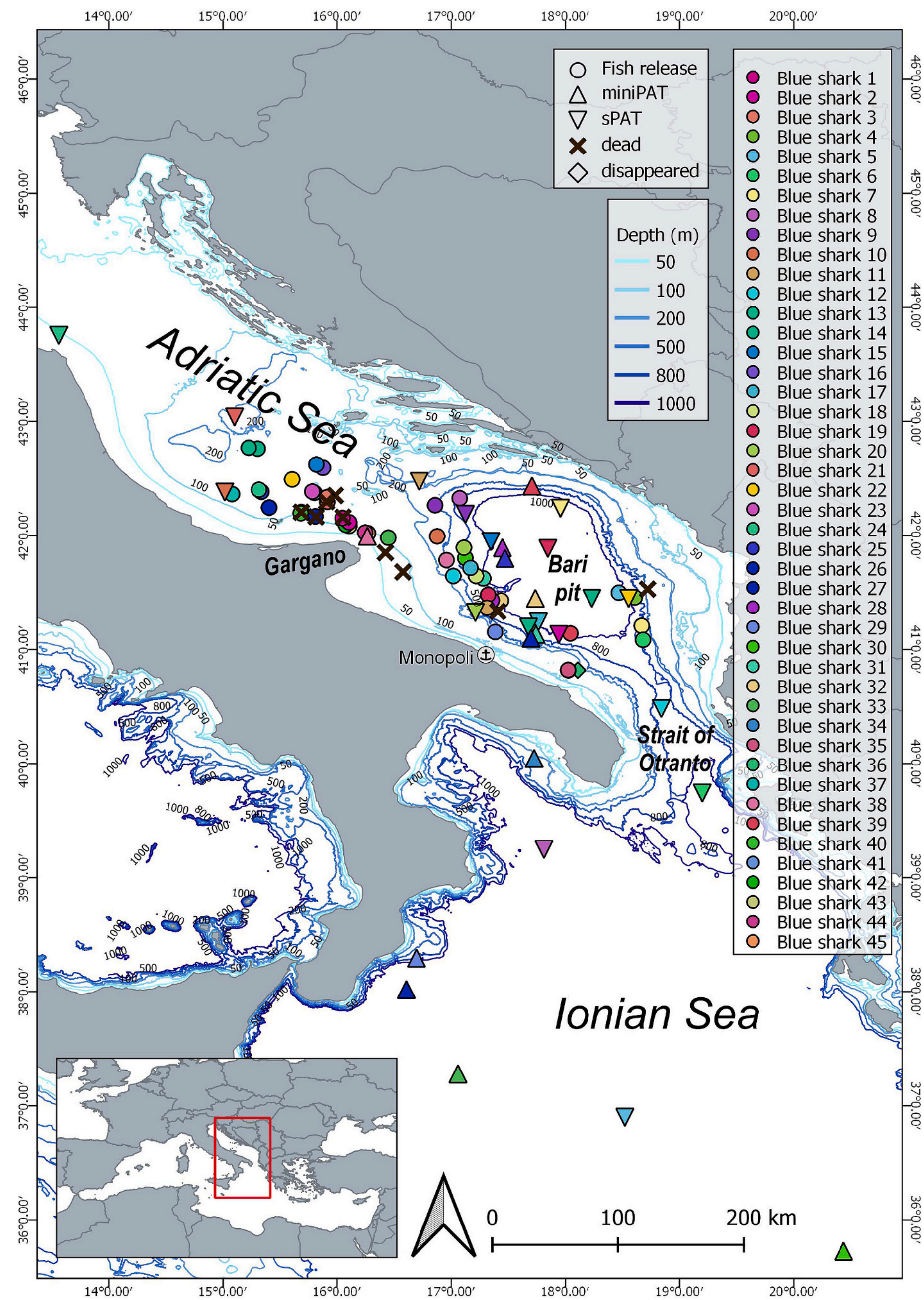

Fig. 6. Locations of release of tagged blue sharks (○) and tags from the specimens (sPAT ▾; miniPAT ▴). **X** corresponds to dead specimens and ◆ to specimens that did not emit signals after release).O. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Capture condition modelling

Permutation importance identified soak time proxy as the dominant predictor by a clear margin, with environmental covariates contributing at more modest levels and on a par with each other. In the final model ensemble, soak time led the ranking, followed by DO, SST, and log-transformed CHL (Fig. 11). Partial dependence profiles illustrate how the predicted probability of condition equalling 1 changes when a given predictor varies, with all other variables averaged out. For soak time, the curve declines steadily: as the duration of the soak increases, the probability of class 1 falls, most sharply after 15 h and then more gradually at higher values (Fig. 12).

The DO profile showed a negative effect, particularly at lower oxygen values. The SST effect P(condition = 1) exhibited a slightly decreasing response, showing a decrease in predicted probability of class-1 condition at higher temperatures, particularly in the upper thermal range (Fig. 12). For CHL, the marginal effect was generally positive beyond low concentrations, showing an increased probability of class-1 condition at higher surface chlorophyll concentrations. The shaded bands around the central PD lines (based on cross-validated variability) demonstrate that the uncertainty surrounding these effects is smaller for soak time, at least at lower values, and greater for the environmental predictors, which is consistent with their relative importance.

The RF model, trained to estimate the probability of condition 1 on the aggregated endpoint (class "1" versus "2–3"), achieved overall good discrimination across cross-validation folds. Cross-validation metrics showed that model performance was stronger and more stable for class 1 than for the aggregated class 2–3. Sensitivity ranged from 0.682 to 0.909 across folds (0.76 ± 0.09), whereas specificity was lower and much

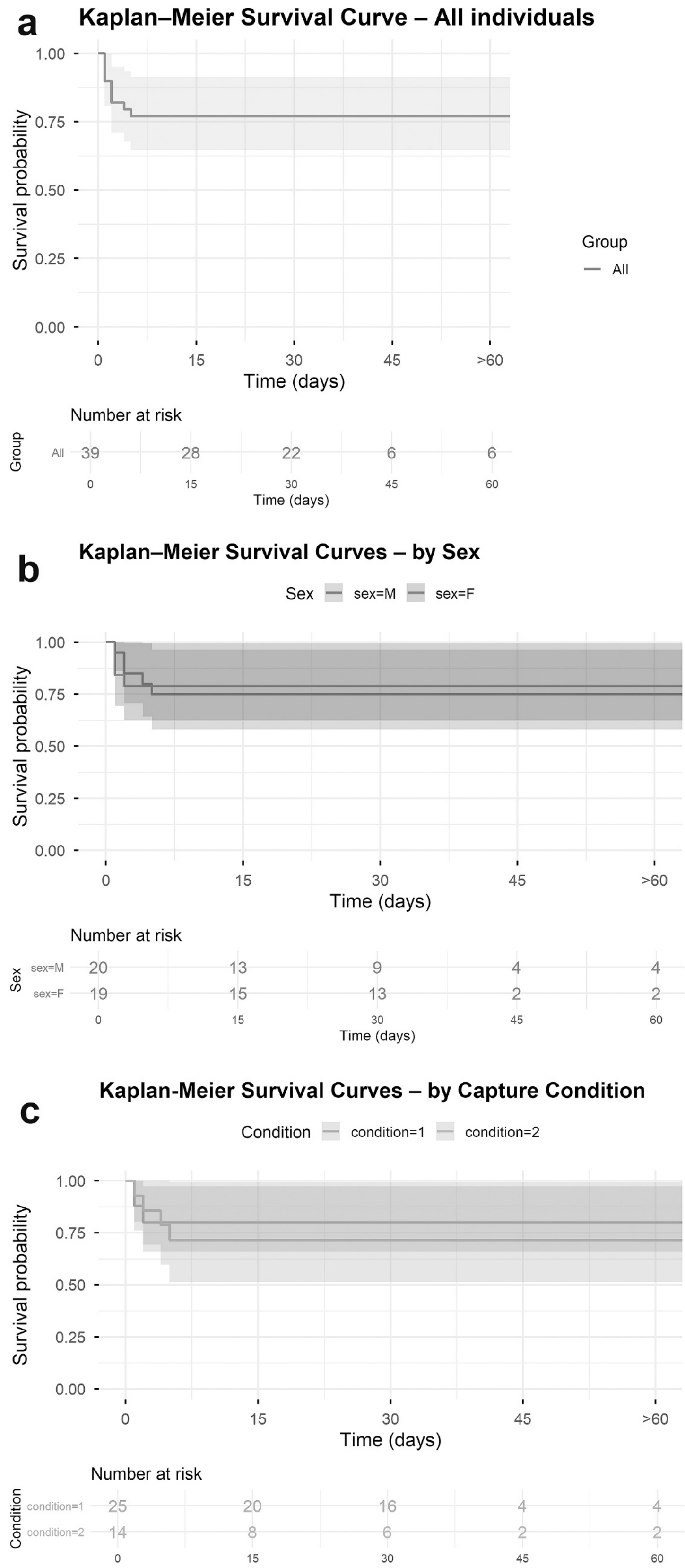

Fig. 7. Post release survival rates (PSR) of tagged sharks estimated by fitting Kaplan–Meier (K-M) survivorship curves. A: all specimens; B: by sex; C: by capture condition.

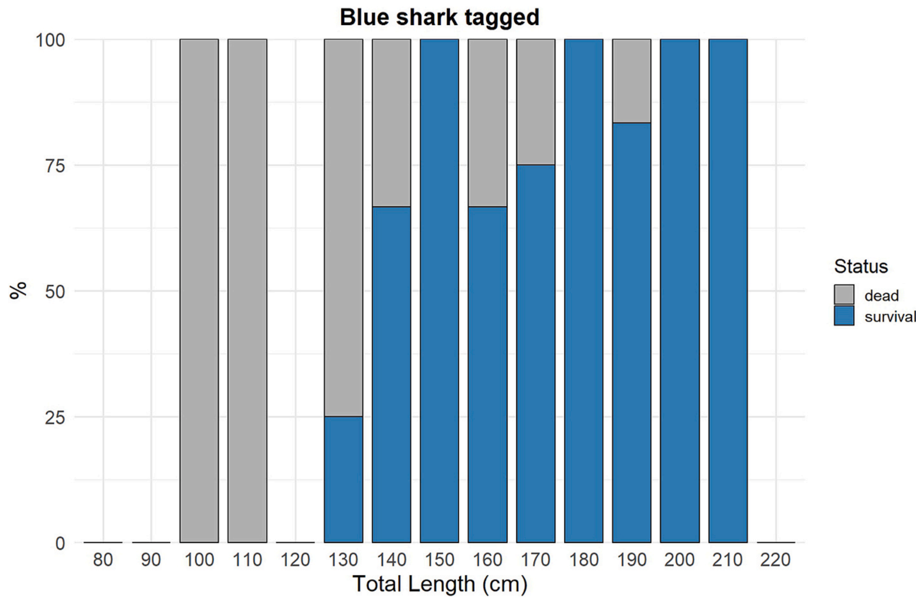

Fig. 8. Survival (in blue) and mortality (in grey) rates (in %) by length class (intervals of 10 cm) of tagged blue sharks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

more variable, ranging from 0.091 to 0.700 (0.41 ± 0.23). Precision–recall curves across cross-validation indicated strong discrimination for the positive class (condition = 1), with high precision maintained across a wide recall range. The PR-AUC ranged from 0.682 to 0.882, with a mean of 0.79 ± 0.08, which is consistent with the imbalanced class structure of the dataset. However, this fold-to-fold variability also indicates that predictions for the aggregated class 2–3 are sensitive to data partitioning, which limits the generalisability of threshold-dependent classification performance for that class. This behaviour is likely related to the reduced representation of condition classes 2–3 in the dataset.

Probability scores were optimised for cross-entropy (log-loss), and inspection of reliability plots (via the scoring diagnostics) did not reveal any systematic miscalibration patterns. Consequently, interpretation is based on probabilistic performance rather than threshold-specific summaries. The predicted probabilities were reasonably well calibrated, particularly for class 1. Accordingly, the model is best interpreted as a probabilistic tool for estimating the likelihood of condition class 1, rather than as a fully symmetric classifier for both outcome groups.

4. Discussion

The multi-year monitoring programme (2019–2024) described here provides one of the most comprehensive empirical datasets available on blue shark bycatch in the Mediterranean (FAO, 2016; Carpentieri et al., 2021) and on capture condition and post-release fate in the southern Adriatic Sea (GSA18). Although coverage varied from year to year, the monitoring covered the core seasonal window for swordfish longline activity (May–November) in the main exploited areas from the local fishery. Furthermore, monitoring coverage, despite showing some variability between years, consistently exceeded the 1% threshold of total FD indicated as the minimum required for reliable bycatch data (FAO, 2016). Although such variability may represent a potential source of bias, sampling followed the spatial distribution of fishing effort, and the use of CPUE and proportional catch metrics likely helped to mitigate these effects and improve comparability across years.

The combination of observer data and pop-up archival telemetry strengthens inference, as on-board observations provide detailed capture-condition information, while satellite tags offer time-resolved evidence of survival after release (Campana et al., 2009; Mucientes et al., 2023). Our results show that mean CPUE remained broadly similar throughout the monitoring period, whereas the percentage of blue sharks landed declined after 2021. The apparent stability of CPUE alongside the reduction in landings may reflect changes in retention practices or operational behaviour, although compliance, awareness, and other socio-operational drivers were not directly measured in this study. Similar patterns have been reported in Mediterranean pelagic longline fisheries, where blue sharks also frequently dominate bycatch assemblages (Bradai et al., 2012; Megalofonou et al., 2005, 2009; FAO, 2016). The decoupling between CPUE and landings highlights the importance of combining onboard observers data with logbook information, since monitoring that relies solely on landed data might underestimate total catch and discard mortality.

Apart from possible changes in retention behaviour, two alternative explanations deserve consideration. First, temporal shifts in the size composition could have influenced landing decisions: if the size distribution of captured sharks shifted towards smaller (or less marketable) size classes after 2021, fishers may have reduced their landings for commercial reasons. However, this hypothesis does not seem plausible, since the total lengths of caught blue sharks did not show significant differences between years (Fig. 9). A second possibility is that changes to fishing gear or operational procedures may have affected the sharks' vulnerability or survival. In our data, however, the gear configuration remained consistent throughout the monitoring period with J-type hooks set at around 30 m, with soak times in the 10–20 h range. This configuration falls within the operational envelope reported for Mediterranean swordfish gear (Carbonara et al., 2023, 2024) and are known to produce substantial pelagic shark bycatch elsewhere (Campana et al., 2009). Nevertheless, increasing release rates alone cannot be interpreted as evidence of a reduced impact if the capture probability remains unchanged. In such cases, understanding the fate of released individuals becomes essential. The telemetry survival estimates reported below, therefore can provide crucial complement to bycatch monitoring (Campana et al., 2016; Francis et al., 2023; Carbonara et al., 2024).

The sPAT tagging experiment yielded an overall short-term survival pattern in which most mortality occurred early (within the first two to four days after release) and an overall survival rate which appears similar to what was observed in the North Pacific, where the survival rate of tagged and released blue sharks was approximately 82% (Musyl and Gilman, 2018).

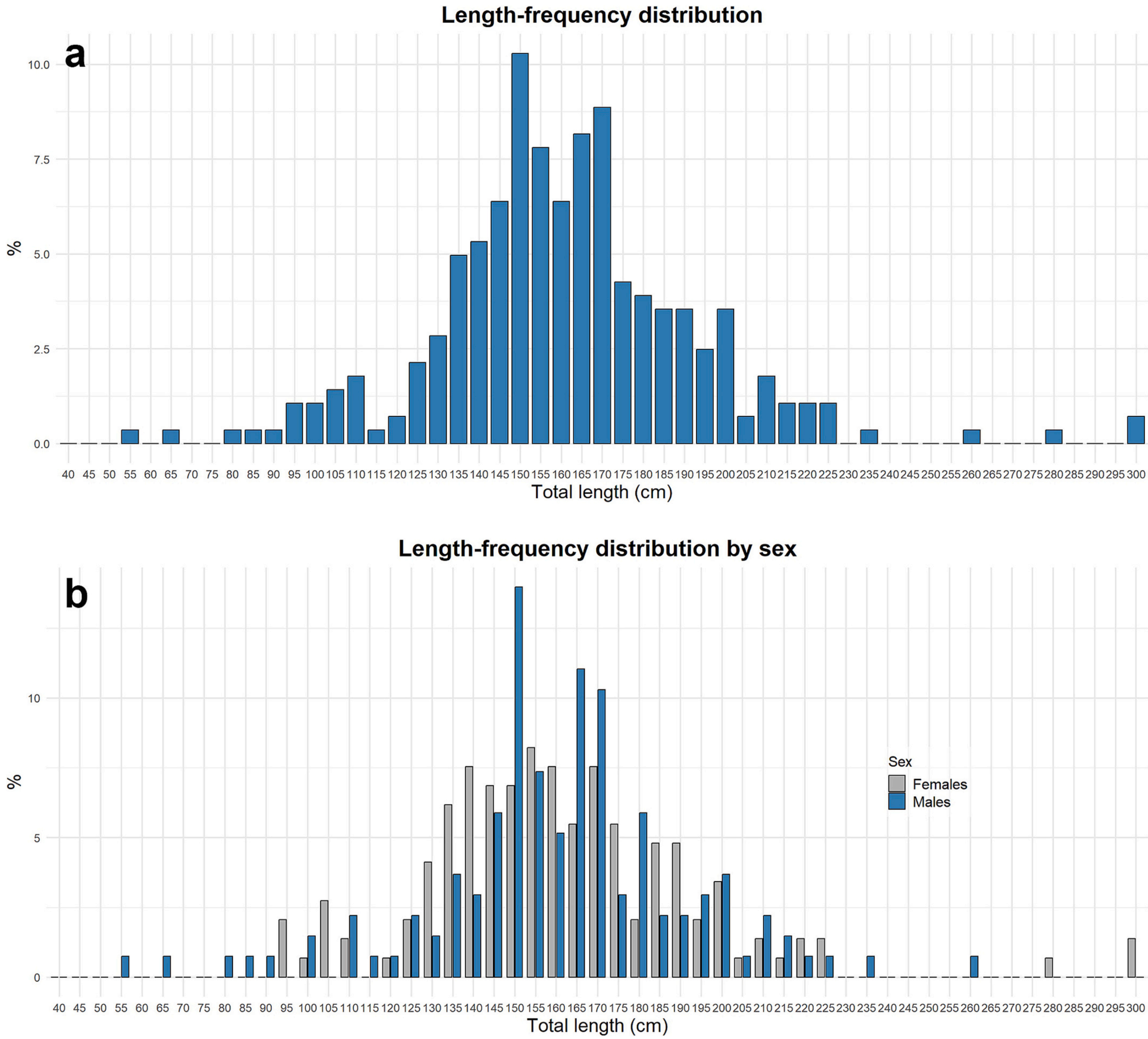

Fig. 9. Frequency distribution of the blue shark length data collected during the monitoring period (2019–2024) through embarkation and monitoring at landing. a: all specimens; b: by sex (females in grey, males in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nonetheless, the estimated survival rate should also be interpreted in light of two potential sources of bias related to the tagging procedure. First, the tagging process required an additional handling time, including manipulation and tag attachment, which could likely impose additional stress beyond that associated with a standard catch-and-release operation and may therefore lead to an underestimation of survival. Conversely, only sharks in condition classes 1 and 2 were tagged, while individuals classified as condition 3 were excluded from tagging, which could inflate the estimated survival rate by removing the most compromised individuals from the monitored sample. This design implies that individuals in the poorest capture condition were not represented in the tagging experiment, which may lead to a positive bias in estimated post-release survival relative to the full bycatch population. These opposing sources of bias suggest that the reported 77% survival rate should be interpreted as an approximation for sharks released in moderate to good condition.

The concentration of mortality in the first days after release is consistent with the expectation that physiological stress and mechanical injury occur during capture, hooking and handling, with sublethal insults either resulting in rapid failure or functional recovery (Campana et al., 2009; Hutchinson et al., 2021). Similar patterns of delayed mortality concentrated in the early post-release period have been documented in Atlantic longline fisheries (Campana et al., 2009). The length-based pattern (most fatalities in TL $<$ 170 cm) indicates that smaller/younger size classes may be more vulnerable to capture stress. This is consistent with other telemetry studies showing that life stage and body size modulate resilience to capture stress (Campana et al., 2009; Schaefer et al., 2021; Francis et al., 2023; Musyl and Gilman, 2018). Recent findings have demonstrated that juvenile blue sharks exhibit significantly different body proportions compared to adult individuals ($>$180 cm TL) (Carbonara et al., 2025b). The authors suggested that this ontogenetic shift is primarily related to optimizing movement and improving swimming efficiency (Carbonara et al., 2025b). In this context, larger specimens may be more capable of rapid post-capture

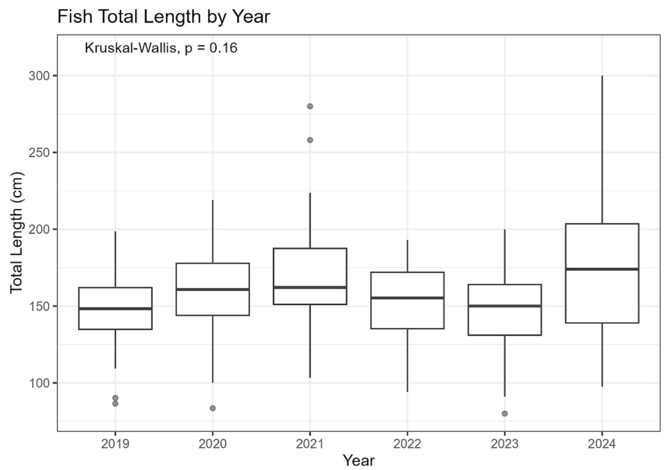

Fig. 10. Box plots of the total length (cm) of blue sharks caught between 2019 and 2024. The central line of each boxplot indicates the median and the boxes on either side represent the quartiles, with the whiskers covering 95% of the values. Outlier values are represented by black dots. There were no significant differences between the years (Kruskal–Wallis $p > 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recovery due to a faster and more efficient oxygen replenishment. On the other hand, smaller individuals may experience a reduced capacity to cope with capture stress due to lower absolute energy reserves and potentially lower aerobic scope with respect to larger individuals. Consequently, physiological disturbances caused by exhaustive exercise, hooking trauma/time, and air exposure may exceed the recovery capacity of juvenile sharks more frequently than in larger specimens. This result could also bring new potential implications as, if smaller sharks are less capable of recovering from capture-related stress, reducing handling time and physical manipulation for these size classes could help improve post-release survival. In particular, rapid in-water release and avoiding lifting small individuals onto the deck may limit additional physiological stress and mechanical injury. In this context, size-aware handling practices could represent a simple mitigation measure in pelagic longline fisheries, where juvenile blue sharks are frequently encountered. Despite the obvious bias in mortality rates resulting from severe handling practices (Campana et al., 2009; Musyl et al., 2009; Musyl et al., 2011; Francis et al., 2023), Musyl and Gilman (2018) showed that handling did not have a significant impact on the blue shark mortality rate. In our work, survival outcomes were strongly influenced by the condition of tagged blue shark at catch.

The Kaplan-Meier absolute survival rates estimated in the present study was 76.9% (95% CI: 64.8–91.4%). This estimate falls within the range described in the literature for pelagic species captured by longline, which varies approximately from 60 to 90% depending on the species, the gear used, the handling method and the environmental context (Musyl and Gilman, 2018). Recent syntheses and methodological reviews (Musyl and Gilman, 2018; Hutchinson et al., 2021) have highlighted that survival estimates are highly dependent on the method used and sensible to selection bias (i.e. which sharks are tagged) and tag failure. Our approach to premature detachments and our conservative classification of motionless tags as mortalities follows accepted practice and helps to avoid optimistic bias. An additional source of uncertainty is represented by the six tags that did not transmit and whose fate could not be determined. Their exclusion from the survival analysis may have influenced the estimated post-release survival. No formal sensitivity analysis was undertaken for these cases, because no auxiliary information was available to support a defensible reassignment of non-transmitting tags to either mortality or survival. This source of uncertainty should therefore be considered when interpreting the results. Comparisons with specific studies in the Atlantic (e.g. Campana et al., 2009) and in the north Pacific (Musyl and Gilman, 2019) suggest broadly similar ranges of survival; however, no formal statistical comparison was conducted, and differences among studies should be interpreted cautiously given differences in methodology, sample composition, and environmental context (Schaefer et al., 2021).

The link between the capture condition of specimens on deck and their subsequent survival is one of the most operationally useful outcomes of this study. Capture condition (three-stage index) appeared to be strongly associated with the survival: with specimens in condition 1 showing substantially higher survival probabilities than those in degraded states. Several studies have linked reflex impairment and physiological stress indicators to delayed mortality (Benoît et al., 2010; Toomey et al., 2025). From a monitoring perspective, rapid on-deck condition assessments may therefore provide a practical proxy for estimating short-term survival probabilities and prioritising handling practices.

A recent study on Mediterranean blue sharks has provided additional physiological context for interpreting capture condition scores. Toomey et al. (2025) described biochemical and haematological profiles of blue sharks following bycatch in the Mediterranean, documenting markers associated with anaerobic exercise, acid–base disturbances and osmoregulatory stress. Such physiological alterations are typically linked to

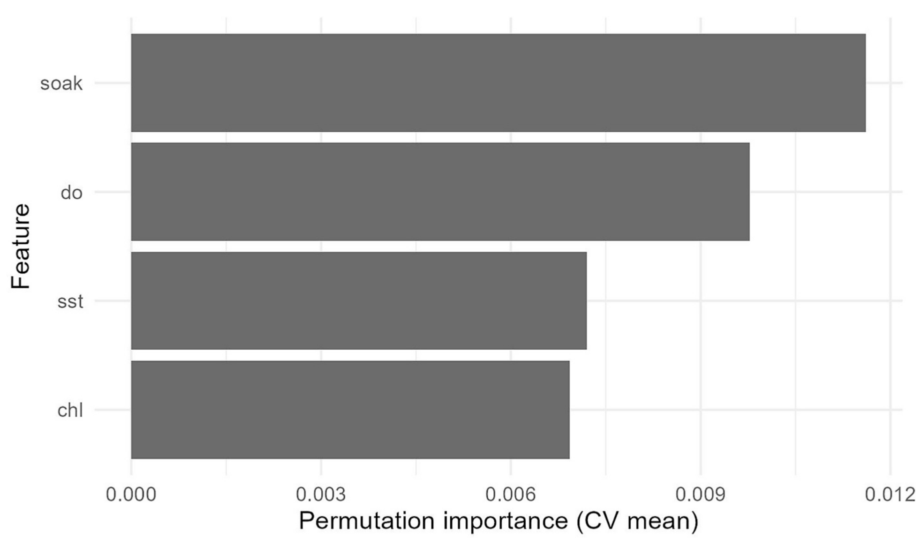

Fig. 11. Feature importance in the random forest analysis. *Soak: soak time, do: dissolved oxygen, sst: sea surface temperature, chl: chlorophyll-a.*

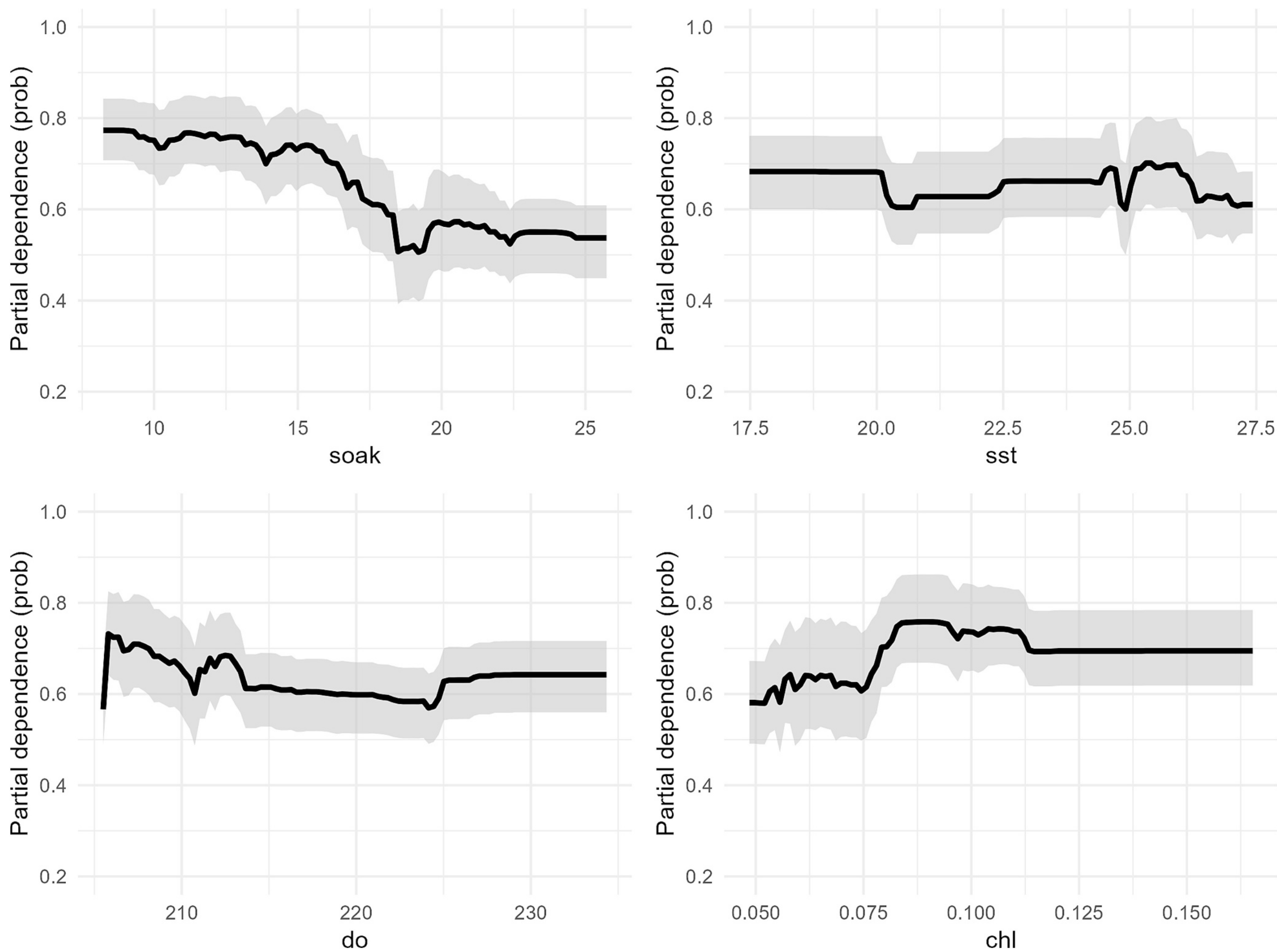

Fig. 12. Partial dependence profiles for soak time (*soak*), dissolved oxygen (*do*), sea surface temperature (*sst*) and chlorophyll-a (*chl*). Grey lines represent the uncertainty.

prolonged exertion and hypoxia during capture events. These physiological findings could represent a mechanistic context for the condition patterns observed in the present study. Sharks exhibiting vigorous responses on deck are likely to have experienced lower physiological disturbance than individuals displaying sluggish or absent reflexes. Therefore, operational factors such as soak time and environmental conditions may contribute to the magnitude of these stress responses, although these mechanisms were not directly measured here. Nevertheless, the physiological evidence supports the use of simple condition indices as integrative indicators of capture stress.

The dominance of soak time as a predictor in the RF model is fully consistent with the physiological literature (Musyl and Gilman, 2018a): longer soak times could provide more time for a shark to struggle, become deeply hooked and experience progressive hypoxia and acidosis. Thus, soak time is both an operational metric and a likely driver of the biochemical derangement observed by Toomey et al. (2025). On the other hand, environmental predictors showed minor effect when compared to soak time. Warmer water increases metabolic demand and can exacerbate oxygen limitations (Vedor et al., 2021; Waller et al., 2024), whereas low-food environments might influence baseline energetic reserves and condition (Vidal et al., 2023). Nonetheless, the uncertainty bands in the partial dependence analysis suggest that these relationships should be interpreted cautiously. Overall, the modelling results highlight the potential importance of operational exposure time relative to environmental variability in shaping capture conditions. The RF classifier performed well under cross-validation (mean PR-AUC ~0.79), with soak time emerging as the dominant predictor, followed by DO, SST and CHL. Several aspects of model interpretation deserve consideration. Firstly, the dominance of soak time reinforces the importance of operational exposure: longer estimated exposure durations, as represented by the soak-time proxy, were associated with a lower probability of sharks being brought on deck in good condition. The partial dependence profile indicated a marked decline in the probability of sharks being in good condition after approximately 15 h of soak time, suggesting a potential inflection point in capture stress accumulation. However, this value should be interpreted in the context of the observed operational range in the dataset. Descriptive statistics (Table 1) show that soak time had a mean of 15.7 ± 4.0 h (range: 8.2–25.7 h), indicating that many fishing operations already occur around or above this value.

Therefore, the identified ~15-hour threshold should not represent an externally imposed management target, but rather a model-derived transition within the range of current fleet practices. Whether reductions in soak time below this level are operationally feasible in Mediterranean swordfish longline fisheries remains uncertain and would require consideration of fishing efficiency, effort distribution, and economic constraints.

The secondary role of environmental covariates highlights opportunities for dynamic spatial management or advisories. Areas and times with suboptimal thermal or productivity conditions could be identified as posing a higher risk of poor capture conditions and thus be targeted for additional mitigation measures. However, the cross-validated uncertainty bands on environmental PDs indicate increased model uncertainty for these predictors relative to soak time. Therefore, any operational recommendations should be implemented cautiously and ideally validated using prospective monitoring. The RF approach estimated calibrated probabilities rather than binary predictions, which is appropriate for management settings where risk gradients matter. In this regard, the model could represent a useful tool in a real-time decision support to help fishers prioritise handling and make informed release decisions. Nevertheless, given the model's limitations, it should be considered locally calibrated and benefit from further training data before being extrapolated to other basins. Specifically, due to the aggregation of condition classes 2 and 3 for modelling purposes, the model effectively contrasts sharks in good condition with those in a compromised state at capture, and therefore does not distinguish weakly responsive individuals from moribund or dead sharks. This aggregation inevitably reduces biological resolution, because sharks showing weak responsiveness at capture may differ substantially from moribund individuals in terms of physiological impairment and subsequent survival potential. Nevertheless, this formulation remains operationally relevant, because distinguishing individuals in clearly good condition from all others is directly aligned with the practical objective of supporting rapid release and mitigation decisions in commercial fishing operations. As a consequence, the model should not be interpreted as predicting a gradient of vitality across all capture-condition states, but rather as identifying the factors associated with the likelihood of sharks arriving on deck in good versus compromised condition.

The findings of this work have several practical implications. Empirically estimating blue shark survival under realistic fishing operations provides a useful benchmark for management in the Mediterranean. By combining observed capture-condition frequencies with condition-specific survival probabilities from telemetry, we estimated that approximately 68% of captured blue sharks may survive after release, a value broadly comparable to the 76.9% estimated by Campana et al. (2016) for the western Atlantic. While the survival rate found in this study does not represent complete mitigation, it indicates that correct handling may contribute to reducing fishing-induced mortality, considering that individuals are released in viable condition. This demonstrates that a substantial proportion of blue sharks caught incidentally by swordfish longliners can survive post-release if handled appropriately. This provides a scientific basis for the development of conservation-oriented release protocols (Wosnick et al., 2023).

The high survival rate estimated here suggests that management measures promoting live release and reducing retention of incidentally caught sharks could contribute to reducing fishing-induced mortality in the Mediterranean. Furthermore, the clear dependence of survival on capture conditions emphasises the crucial importance of training fishers in handling and rapid release techniques. Simple, low-cost measures, such as keeping the shark in the water while removing the hook, minimising air exposure, and cutting the leader close to the hook if the shark is deeply hooked, could further enhance survival beyond the baseline estimate of 68% (Hutchinson and Bigelow, 2019).

These recommendations are consistent with existing best-practice guidelines developed for pelagic longline fisheries, which emphasise the importance of minimising handling time, avoiding bringing sharks on deck whenever possible, and possibly performing hook removal with the animal remaining in the water (FAO, 2023; Gilman et al., 2016). Moreover, the use of appropriate dehooking devices and line-cutting tools has also been recommended to facilitate rapid release and reduce injury during handling (Hutchinson and Bigelow, 2019). However, such handling recommendations should be considered as evidence-informed priorities for future operational testing rather than demonstrated outcomes of this study.

Additional mitigation measures, such as reducing longline soak time, could potentially further improve post-release survival by limiting exhaustion and physiological stress before release. However, the adoption of shorter soak times in commercial Mediterranean swordfish fisheries may be constrained by operational and economic considerations, including fishing efficiency, fuel consumption, and logistical constraints associated with large-scale longline operations (Gilman et al., 2016; Musyl and Gilman, 2018).

Integrating survival estimates into bycatch management frameworks provides a quantitative tool for evaluating policy effectiveness. If future monitoring continues to document stable or declining bycatch rates alongside rising live release rates, managers could infer a genuine reduction in population-level fishing mortality. Conversely, if bycatch rates remain stable but survival indicators deteriorate, this would signal that handling protocols and operational conditions, such as soak time, need to be emphasised more strongly. Thus, the present results offer a pathway for adaptive management: by combining field-based survival data, modelled capture condition probabilities, and fisher participation, management authorities can refine mitigation measures iteratively.

The demonstrated feasibility of combining monitoring, fisher cooperation (Santin-Muriel et al., 2022), and satellite tagging shows that effective mitigation can be achieved in small-scale and semi-industrial fisheries, provided there is appropriate training and stakeholder engagement. In this context, catch-and-release guided by empirically derived survival estimates not only represents a conservation measure but also an opportunity to foster collaboration and trust between fishers and scientists in their shared goal of sustaining pelagic ecosystems (Wosnick et al., 2023; Santin-Muriel et al., 2022; Poisson et al., 2024).

The combined evidence from monitoring, telemetry and physiological studies suggests the following harvest management strategies: i) operational mitigation: shortening soak times and prioritising quick retrieval could help in reducing injury severity while potentially increasing survival; ii) refined release guidelines linked to on-deck condition can be useful to inform handling and release decisions; iii) pairing telemetry with physiological sampling could provide mechanistic markers to refine survival predictions. Overall, these results provide fishery-specific quantitative evidence that post-release survival of blue sharks (*Prionace glauca*) in Mediterranean swordfish longline fisheries is strongly condition-dependent and influenced by operational factors. This highlights that management effectiveness should be evaluated in terms of total fishing-induced mortality rather than landings alone. The present findings therefore support the implementation of practical mitigation measures targeting capture and handling practices, particularly those aimed at reducing exposure time and improving release outcomes in this species.

5. Conclusion

This study is the first to provide an integrated assessment of blue shark (*Prionace glauca*) bycatch and post-release survival in the southern Adriatic Sea, combining multi-year monitoring, fisherman cooperation, and satellite tagging. Catch rates remained stable from 2019 to 2024, while landings declined after 2021, a pattern consistent with changes in retention behaviour. The tagging results indicated a post-release survival of approximately 77%, with the majority of mortalities occurring within four days. Survival appeared to be strongly linked to capture condition and body size. Integrating capture-condition frequencies with telemetry-derived rates suggests that aproximately 68% of captured sharks may survive if handled and released properly, although the lower bound of the bootstrap 95% CI (55.4%) highlights substantial uncertainty and a more precautionary scenario relevant for conservation planning.

The Random Forest model identified soak time as the variable most strongly associated with capture condition, while environmental variables showed weaker effects. These findings suggest that operational exposure may influence the likelihood of sharks being retrieved in good condition. Overall, our results provide new empirical data on blue shark bycatch dynamics, post-release survival, and factors associated with capture condition in Mediterranean longline fisheries, offering a practical framework to evaluate and refine bycatch mitigation strategies.

CRediT authorship contribution statement

Pierluigi Carbonara: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Andrea Bellodi:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Giulia Prato:** Writing – review & editing, Resources, Conceptualization. **Simone Niedermüller:** Writing – review & editing, Resources, Methodology, Conceptualization. **Alessandro Buzzi:** Writing – review & editing, Methodology. **Cosmidano Neglia:** Writing – review & editing, Methodology. **Lola Toomey:** Writing – review & editing, Visualization, Methodology. **Massimiliano Bottaro:** Writing – review & editing, Methodology. **Maria Cristina Follesa:** Writing – review & editing, Methodology. **Walter Zupa:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no conflicts of interest associated with this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2026.111939.

Data availability

Data will be made available on request.

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