Acta Ichthyologica et Piscatoria 56, 2026, 483–490 | DOI 10.3897/aiep.56.213701

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ACTA ICHTHYOLOGICA ET PISCATORIA

Interactions of large pelagic sharks (Elasmobranchii) with capture-based tuna aquaculture and salmon farming in the Mediterranean Sea

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Academic editor: Adnan Tokaç ♦ **Received** 29 August 2026 ♦ **Accepted** 20 October 2026 ♦ **Published** 4 November 2026

Citation: Ugarković P, De Maddalena A, Žuvić L (2026) Interactions of large pelagic sharks (Elasmobranchii) with capture-based tuna aquaculture and salmon farming in the Mediterranean Sea. Acta Ichthyologica et Piscatoria 56: 483–490. https://doi.org/10.3897/aiep.56.213701

Abstract

Interactions between large pelagic sharks and marine aquaculture remain poorly documented in the Mediterranean Sea. We report six cage-entry events involving blue sharks, *Prionace glauca* (Linnaeus, 1758), and shortfin makos, *Isurus oxyrinchus* Rafinesque, 1810, associated with capture-based Atlantic bluefin tuna aquaculture and Atlantic salmon farming between 2018 and 2026. Records were compiled from direct observations, information provided by personnel involved in fishing and aquaculture operations, and original photographic and video material. Four cage-entry events occurred through breaches in the cage netting, while two blue sharks were captured incidentally with tuna in purse seines and subsequently transferred into transport cages. Three sharks were released alive and three died after becoming entangled in cage netting. Evidence of feeding was recorded in five of the six cage-entry events. The records demonstrate two distinct pathways of shark entry into aquaculture cages: entry through breaches in cage netting and incidental transfer from purse seines into tuna transport cages. Although the opportunistic nature of the observations precludes estimation of interaction frequency, the documented mortalities highlight the importance of systematic reporting, rapid-release procedures, and mitigation measures aimed at reducing shark entry and entanglement.

Keywords

blue shark, cage breach, entanglement, incidental transfer, shortfin mako

Introduction

Tuna farming is a relatively recent development in the Mediterranean Sea, with the first farm established in 1995 (Galaz and De Maddalena 2004). Atlantic bluefin tuna, *Thunnus thynnus* (Linnaeus, 1758), farming subsequently expanded throughout the Mediterranean, with farming facilities established in Spain, Italy, Malta, Croatia, Türkiye, Tunisia, Cyprus, Greece, Libya, and other parts of the Mediterranean basin. Major farming clusters have been reported around Cartagena in Spain, Naples in Italy, and Zadar in Croatia (Miyake et al. 2003; Jelić Mrčelić et al. 2023). Mediterranean tuna aquaculture is predominantly capture-based; wild tuna are caught using purse seines, transferred into transport cages, and subsequently towed to farming sites for fattening or longer-term rearing (Jelić Mrčelić et al. 2023).

Various tuna species, ranging from small-bodied species to the Atlantic bluefin tuna, form part of the diet of

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several large pelagic sharks, including the great white shark, *Carcharodon carcharias* (Linnaeus, 1758) (see Kabasakal 2014; Boldrocchi et al. 2017); the shortfin mako, *Isurus oxyrinchus* Rafinesque, 1810 (see Preti et al. 2012; Biton Porsmoguer et al. 2014); and the blue shark, *Prionace glauca* (Linnaeus, 1758) (see Preti et al. 2012; Klarian et al. 2018). Because tunas constitute prey of these shark species and capture-based aquaculture temporarily concentrates large numbers of tuna during capture, transfer, towing, and rearing, these operations provide opportunities for shark–aquaculture interactions (Galaz and De Maddalena 2004; Kabasakal and Gedikoğlu 2015; Bath et al. 2023).

More recently, Atlantic salmon, *Salmo salar* Linnaeus, 1758, farming was introduced at Lukovo Šugarje in the Velebit Channel, northern Adriatic Sea, Croatia (Milošević et al. 2024), following authorization for the introduction of the species for aquaculture in 2021. The farming cages are located over water depths of approximately 60 m (Šinko 2025).

Globally, interactions between sharks and marine aquaculture facilities include their presence or aggregation around farms, predation on cultured fish, cage penetration, entrapment, and entanglement. Potential consequences for both aquaculture operations and shark conservation are poorly understood and underreported (Bath et al. 2023).

Only a few cases of sharks entering or becoming trapped in tuna cages have previously been reported from the Mediterranean Sea. Galaz and De Maddalena (2004) reported two blue sharks that entered a tuna cage being towed between Italy and Spain in 2001, a 40-kg shortfin mako that entered a tuna cage between the Balearic Islands and Murcia, Spain, in 2002, and an estimated 500-cm female great white shark that entered a tuna cage off Tripoli, Libya, in June 2002. In October 2009, a 480-cm female great white shark was reported trapped in a tuna cage off Mahdia, Tunisia (De Maddalena and Heim 2012). Besides sharks, other elasmobranchs have also been reported entering aquaculture cages, including five bull rays, *Aetomylaeus bovinus* (Geoffroy Saint-Hilaire, 1817), that accidentally entered fish cages during a routine net replacement operation in İskenderun Bay, Türkiye (Akyol et al. 2022).

This study documents six cage-entry events involving blue sharks and shortfin makos during capture-based tuna aquaculture or salmon farming operations in the Mediterranean Sea, and examines the operational pathways associated with these events and their potential implications for shark conservation and mitigation practices.

Materials and methods

Records of interactions between large pelagic sharks and capture-based tuna aquaculture or salmon farming operations were compiled from direct observations by the authors and from information provided by personnel involved in commercial fishing, tuna transfer, cage towing, and fish-farming operations. Original photographic and video material associated with the reported events was examined by the authors.

Species identification followed Compagno (1984a, 1984b, 2001) and De Maddalena (2024) and was based on diagnostic external morphological characters visible during direct observation or in the available photographic and video material. Sex was determined from the presence or absence of claspers when the pelvic region was visible. For each included record, available information on date, locality, type and stage of the fishing or farming operation, circumstances of the interaction, feeding behavior, outcome, and supporting photographic or video documentation was compiled.

Total length (TL) was estimated by personnel involved in the fishing or farming operations or by the authors from direct observations, photographs, or video footage. Where possible, the authors used persons or objects of approximately known dimensions as size references. Estimates are approximate and are reported as ranges where appropriate. Values provided by personnel are explicitly identified as reported estimates. Body mass was estimated for only one specimen by one of the authors (LŽ), through direct observation after retrieval, and is therefore presented in the corresponding case description rather than in Table 1. Selected low-quality photographs, including images taken at dusk and still frames extracted from video recordings, were processed using the free online image editor Photopea. Minor adjustments to contrast and sharpness were applied to improve visual clarity for presentation in this study. Cages used to transport live Atlantic bluefin tuna by towing are referred to as “tuna transport cages”, or simply “transport cages” where the context is clear.

Results and discussion

On 3 June 2018, a male blue shark, *Prionace glauca*, was incidentally captured and transferred with tuna into a tuna transport cage in the Jabuka Pit. It consumed several juvenile Atlantic bluefin tuna, *Thunnus thynnus*, intended for farming while the towing vessel *Trapa* remained stationary, but became entangled and died after towing commenced. Later that day, divers retrieved it and brought it aboard the towing vessel (Fig. 1). One of the authors (LŽ) directly observed the specimen after it had been retrieved and brought aboard the towing vessel and estimated its TL at 250 cm and its body mass at 120 kg. On 4 June 2018, a blue shark entered a tuna transport cage in the Jabuka Pit through a breach in the bottom netting, reportedly made by the shark during the night. Personnel reported that it consumed only the viscera of two tuna, leaving their carcasses on the cage bottom. It was released alive after a diver cut the netting away from the floating collar, lowered the handrail, and positioned himself in the shark’s path to redirect it through the opening (Fig. 2). The shark swam away apparently unharmed.

Table 1. Summary of shark cage-entry events documented in this study. Species: blue shark, *Prionace glauca*; shortfin mako, *Isurus oxyrinchus*.

No.	Date	Locality	Species	Sex	Estimated TL [cm]	Mode of entry	Feeding	Outcome
1	3 June 2018	Jabuka Pit, Central Adriatic Sea	Blue shark	Male	250	Captured in a tuna purse seine and transferred into a transport cage	Consumed several juvenile Atlantic bluefin tuna	Died after becoming entangled in the cage netting
2	4 June 2018	Jabuka Pit, Central Adriatic Sea	Blue shark	Not determined	Not estimated	Entered the cage through a breach	Consumed the viscera of two Atlantic bluefin tuna	Released alive
3	20 June 2018	Jabuka Pit, Central Adriatic Sea	Blue shark	Not determined	250†	Captured in a tuna purse seine and transferred into a transport cage	Consumed one Atlantic bluefin tuna	Released alive
4	11 July 2024	Lukovo Šugarje, Northern Adriatic Sea	Blue shark	Female	200–250†	Entered the cage through a breach	Atlantic salmon remains found inside the cage	Released alive
5	1 June 2026	Libyan waters	Shortfin mako	Female	160–200	Entered the cage through a breach	No feeding reported	Died after becoming entangled in the cage netting
6	29 June 2026	Strait of Otranto	Shortfin mako	Female	320–340	Entered the cage through a breach	Remains of at least one Atlantic bluefin tuna found inside the cage	Died after becoming entangled in the cage netting

† Total lengths marked with this symbol were reported by fishers, eyewitnesses, or farm personnel. All other available total-length estimates and all sex determinations were made by the authors. Total length was estimated from video footage in case 5 and from photographs in case 6.

Figure 1. The male blue shark, *Prionace glauca*, estimated at approximately 250 cm TL, retrieved from a tuna transport cage in the Jabuka Pit, central Adriatic Sea, on 3 June 2018, after becoming entangled in the cage netting (photograph by Luka Žuvić).

On 20 June 2018, in the Jabuka Pit, another blue shark, estimated by eyewitnesses to be approximately 250 cm TL, was captured with tuna in a purse seine and subsequently transferred with the catch into a transport cage. While inside the cage, the shark consumed one tuna. Personnel of Pelagos d.o.o. filmed the shark in the cage (Fig. 3) and subsequently released it alive. On 11 July 2024, a female blue shark was observed inside a cage holding Atlantic salmon, *Salmo salar*, at Lukovo Šugarje, Croatia (ca. 44°26.4′N, 15°10.8′E). The shark had entered through a breach in the cage netting (Fig. 4A). Remains of an Atlantic salmon were found inside the cage following the interaction (Fig. 4B). Farm personnel photographed the shark while it was swimming inside the cage and estimated its total length at 200–250 cm (Fig. 4C). The shark was subsequently released alive by cutting an approximately 10-m section of the netting to provide an exit.

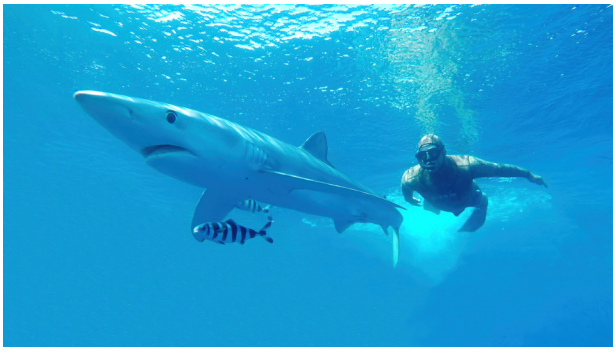

Figure 2. A blue shark, *Prionace glauca*, inside a tuna transport cage in the Jabuka Pit, central Adriatic Sea, on 4 June 2018, after entering through a breach in the bottom netting. The shark was subsequently released alive (photograph by Marin Rakić).

On 1 June 2026, the Maltese-flagged vessel *Mirkut* was towing a tuna transport cage through Libyan waters towards a farming facility in Malta. A female shortfin mako, *Isurus oxyrinchus*, entered the cage through

Figure 3. Still from a video of a blue shark, *Prionace glauca*, estimated at approximately 250 cm TL, swimming inside a tuna transport cage in the Jabuka Pit, central Adriatic Sea, on 20 June 2018. The shark had been captured together with Atlantic bluefin tuna, *Thunnus thynnus*, in a purse seine, transferred into the cage, and was subsequently released alive (video by Nedo Bausović).

a breach in the netting and subsequently became entangled. The shark was found dead by the crew. A short video recorded after retrieval documents the specimen (Fig. 5A); although the footage does not permit precise measurement, the authors estimated its total length at 160–200 cm. On 29 June 2026, a female shortfin mako entered a tuna transport cage through a breach in the netting in the Strait of Otranto during the night, while the vessel *Neptun* was towing it from Italy to Croatia. The shark became entangled and died, and was retrieved aboard using a crane. Although the crew estimated its TL at approximately 400 cm, photographic comparison with objects of known size yielded an estimate of 320–340 cm (Fig. 5B). The photographs also showed partially dusky coloration on the underside of the snout and lower jaw (Fig. 5C), resembling the "marrajo criollo" form described by Moreno and Morón (1992); similar coloration was subsequently documented in a live Mediterranean specimen by De Maddalena et al. (2023). Remains of at least one Atlantic bluefin tuna were found inside the cage (Fig. 5D). Information on the six documented cage-entry events is presented in Table 1.

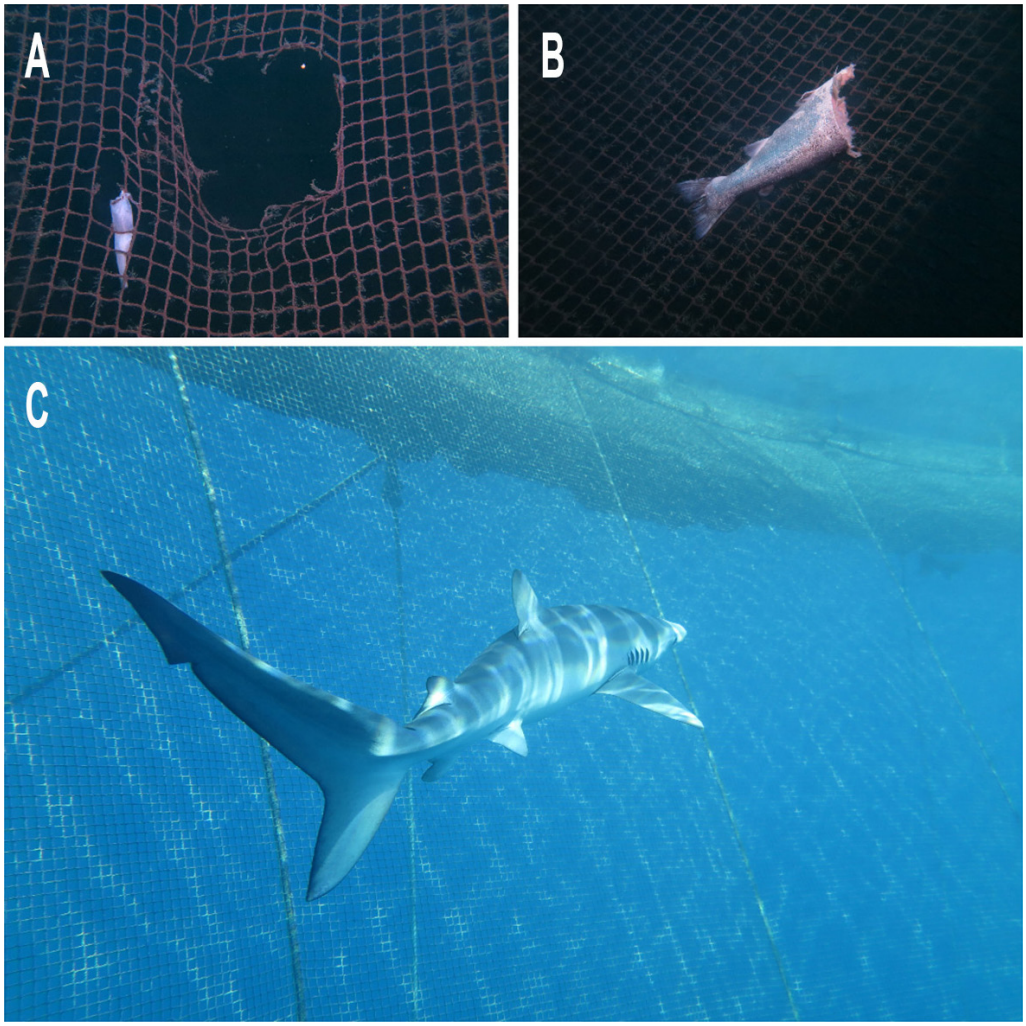

Figure 4. (**A**) The breach in the cage netting through which a female blue shark, *Prionace glauca*, entered a cage containing Atlantic salmon, *Salmo salar*, at Lukovo Šugarje, Croatia, on 11 July 2024. (**B**) Remains of an Atlantic salmon found inside the cage following the interaction. (**C**) The female blue shark, estimated at 200–250 cm TL, swimming inside the cage (photographs by Đani Iglić).

Figure 5. (**A**) Still from a video of a female shortfin mako, *Isurus oxyrinchus*, estimated at 160–200 cm TL, found dead on 1 June 2026 in Libyan waters after entering a tuna transport cage and becoming entangled in the netting. (**B**) The female shortfin mako, *Isurus oxyrinchus*, estimated at 320–340 cm TL, found dead on 29 June 2026 in the Strait of Otranto after entering a tuna transport cage and becoming entangled in the netting. (**C**) Close-up of the same specimen showing the partially dusky coloration of the underside of the snout and lower jaw. (**D**) Remains of an Atlantic bluefin tuna, *Thunnus thynnus*, found inside the transport cage following the interaction with the shortfin mako documented in the Strait of Otranto. Credits: A, video by Rino Glorius; B–C, photographs by Danijel Kolega; D, photograph by Nedo Bausović.

Personnel involved in tuna capture, transfer, and towing operations also reported blue sharks and shortfin makos swimming near transport cages without entering them, with some observations supported by video footage. These encounters were not included as individual case records because complete event-level information was unavailable and observations were not collected systematically. They suggest that interactions extend beyond cage entry, but do not allow estimation of encounter frequency.

The first author and staff of Kali Tuna d.o.o. also observed a great white shark, *Carcharodon carcharias*, estimated at approximately 5 m TL, approaching the tugboat *Voluja* twice in the Jabuka Pit on 12 June 2012, shortly after Atlantic bluefin tuna had been transferred into a transport cage (P. Ugarković, pers. obs.). Comparable associations between great white sharks and tuna-related fishing or farming operations have previously been reported in the Mediterranean (De Maddalena and Heim 2012; Kabasakal 2014). Notably, Soldo and Dulčić (2005) reported the capture of a great white shark in a tuna purse seine in the same general area as the personal observation described above, during a similar tuna-fishing operation.

The documented cage-entry events, together with the additional observations discussed above, illustrate three operationally distinct pathways through which sharks may interact with fishing and aquaculture operations: (1) approaching vessels or cages without entering them; (2) entering cages through breaches in the netting; or (3) being captured incidentally together with tuna in purse seines and subsequently transferred into transport cages with the catch. The six documented cage-entry events represent the latter two pathways, whereas the first is illustrated by the additional observations. These pathways represent different mechanisms of interaction and may therefore require different mitigation approaches.

All shark species reported here were classified as Critically Endangered in the 2016 IUCN Mediterranean regional assessments (Soldo et al. 2016; Sims et al. 2016; Walls and Soldo 2016). Given the regional conservation status of these species, interactions between sharks and

fish-farming operations should be systematically monitored so that trapped or entangled individuals can be detected and, where feasible and safe, released as rapidly as possible. More active shark species have higher consumption rates of oxygen (Howe 1988). Shortfin mako and great white sharks exhibit some of the highest metabolic or oxygen consumption rates reported for sharks (Sepulveda et al. 2007; Ezcurra et al. 2012). In protective gill nets off Natal, South Africa, only 6% of shortfin makos (Cliff et al. 1990) and 16% of great white sharks (Cliff et al. 1989) were found alive, highlighting the importance of releasing entangled individuals as rapidly as possible.

Shark entry into cages, as well as their presence in the vicinity of cages during tuna-related operations, may reflect a transient response to cues associated with injured or dead fish, rather than attraction to live tuna or to the cage structure itself. Similar associations between shark presence and aquaculture-related fish mortality have been reported elsewhere in the Mediterranean. Ergüden et al. (2020) documented several sandbar sharks, *Carcharhinus plumbeus* (Nardo, 1827), around fish cages during the removal of large quantities of wounded and dead cultured fish, while Akyol and Şen (2022) observed sandbar sharks approaching a diver and sporadically attempting to attack a cage during the removal of dead farmed fish. Although these observations involve a different shark species and different farming systems, they support the possibility that food-related cues associated with injured or dead cultured fish may increase the likelihood of short-term shark presence and interaction around aquaculture operations. Shark responses to aquaculture facilities, however, appear to be context dependent. Barash et al. (2018) documented recurrent seasonal presence of sandbar sharks around open-sea fish cages in the eastern Mediterranean over several years. In contrast, using acoustic telemetry, Huveneers et al. (2022) found no evidence that a low-biomass tuna pen used for tourism increased shark abundance or residency in South Australia. In the present study, most interactions occurred during or immediately after tuna capture, transfer, or towing operations, when tuna were densely aggregated and when injured or dead fish could be present. Such conditions differ substantially from routine husbandry conditions and may generate stronger short-term feeding-related cues.

Strong polyethylene terephthalate (PET) monofilament, semi-rigid or tightly stretched net walls, and robust containment barriers have been proposed as measures to reduce predator entry into cages in marine aquaculture (Bath et al. 2023). Incidental transfer of sharks from purse seines into transport cages might instead be reduced by detecting and, where feasible and safe, releasing sharks before the catch is transferred. Continuous monitoring, prompt removal of dead or injured fish, and rapid-release procedures for sharks that enter cages are likely to be relevant across interaction types (Bath et al. 2023). The effectiveness of these measures for the species and farming systems considered here should, however, be specifically evaluated.

The records presented here show that interactions between large pelagic sharks and capture-based tuna aquaculture or other marine fish-farming operations in the Mediterranean can arise through several distinct pathways and may result in feeding opportunities, entrapment, and mortality. Because the observations were opportunistic and observation effort was not standardized, they cannot be used to estimate interaction frequency or to demonstrate attraction to farming operations. Nevertheless, the occurrence of fatal cage interactions involving regionally critically endangered shark species highlights the need for systematic reporting, rapid-release procedures, and evaluation of cage designs and operational practices aimed at reducing shark entry, entanglement, and mortality.

Acknowledgments

The work of the PhD student Luka Žuvić was supported by the Young researchers' career development project–training of doctoral students of the Croatian Science Foundation (NPOO-DOK-2023-10). The authors are grateful to Branimir Ivoš, Đani Iglić, Marin Rakić, Nedo Bausović, Danijel Kolega, and Rino Glorius for providing information gathered through communication with fishing and aquaculture personnel and vessel crews, and/or photographic and video material supporting the records presented in this study. The authors also thank the image and video contributors for permission to reproduce their material, and Eric Glenn Haenni for English-language editing of the manuscript. Alessandro De Maddalena thanks Alessandra, Antonio, and Phoebe for their support and love.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

Ethical approval was not required for this study because no sharks were captured, handled, or killed for research purposes; all observations and visual material originated from commercial fishing and aquaculture operations.

Artificial Intelligence (AI) use

Generative AI was used to assist with English-language editing and stylistic refinement. No AI tools were used to generate or analyze study data. All scientific content, interpretations, references, and final wording were reviewed and approved by the authors.

Funding

This research was fully supported by the Croatian Science Foundation under the project HRZZ-IP-2022-10-7232 Enhancing Environmental Performance of Net-Pen Marine Aquaculture.

Author contributions

Conceptualization: PU, AD; Methodology: PU, AD; Validation: PU, AD, LŽ; Investigation: PU, LŽ; Resources: PU, LŽ; Data curation: PU, AD, LŽ; Writing – original draft: AD; Writing – review and editing: PU, AD, LŽ; Visualization: PU, AD, LŽ; Supervision: AD; Project administration: LŽ.

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Data availability

All data supporting the findings of this study are included in the article. Additional photographic and video material supporting the reported records is available from the corresponding author upon reasonable request, subject to permission from the original copyright holders.