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Risks associated with the spatial overlap between humpback dolphins and fisheries in Sindhudurg, Maharashtra, India

Ketki Jog[1,*], Dipani Sutaria[1], Alana Grech[1], Rhondda Jones[2], Mihir Sule[3], Isha Bopardikar[4], Helene Marsh[1]

[1]College of Science and Engineering, James Cook University, Townsville, QLD 4811, Australia
[2]College of Public Health, Medical and Veterinary Sciences, James Cook University, Townsville, QLD 4811, Australia
[3]The Konkan Cetacean Research Team, Dadar West, Mumbai 40028, Maharashtra, India
[4]Department of Biology, Indian Institute of Science Education and Research, Tirupati 51707, Andhra Pradesh, India

ABSTRACT: The Sindhudurg coast in Maharashtra, India, supports diverse fisheries and is a vital habitat for the Indian Ocean humpback dolphin *Sousa plumbea*, a species found nearshore along the west coast of India. Here, dolphins cause economic losses to fishermen by competing for catch and damaging fishing gear. Dolphins are also affected by entanglement in or ingestion of parts of fishing nets. There is a need for a systematic assessment of the distribution of risks to dolphins and the specific fisheries most impacted by interactions with dolphins. To bridge this information gap, we (1) analysed the behaviour and locations of dolphin groups in the absence and presence of fishing vessels (2012–2015) and (2) mapped the spatial overlap of dolphins and fishing vessels (2014–2015) to determine high-risk areas for dolphins. We observed 175 dolphin groups, of which 75 groups (43%) engaged in foraging behaviours. Dolphins occurred in approximately 50% (164 km^2) of the total survey area, and fishing vessels were observed in 100% of the total survey area (333 km^2). The proportion of dolphin groups engaged in foraging behaviours was significantly higher when fishing vessels were present compared to when absent. Gillnet (55%) and trawl (32%) accounted for the majority of observed fishing vessels when dolphins were present. Gillnet vessels had a 95% spatial overlap with dolphin habitat, and trawl and purse-seine vessels each had 86%. We identified 8 high-risk areas that were within ~500 m of the coastline, coinciding with high-density dolphin habitat near estuaries. These results have the potential to inform marine mammal conservation and fishery management in Sindhudurg.

KEY WORDS: *Sousa plumbea* · Indian Ocean humpback dolphin · Interactions · Fisheries · Spatial distribution · Foraging behaviour · India · Sindhudurg · Indian Ocean

1. INTRODUCTION

The interactions between marine mammals and fisheries resulting from overlaps in resource and space use, such as marine mammals competing for catch and damaging fishing gear, and bycatch or unintended entanglement of marine mammals in fishing gear, can lead to adverse effects on both marine mammal populations and fishery-based livelihoods (Read 2008). Although fishing operations may facilitate access of dolphins to prey, they can also increase the risk of incidental injuries, entanglements and unintended captures or bycatch (Brownell et al. 2019). Resource competition can also affect the distribution and behavioural ecology of populations in the long term (Bonizzoni et al. 2021). Dolphin entanglements in and foraging from fishing gear can lead to considerable economic losses to fishers as a result of gear

*Corresponding author: ketki.jog@my.jcu.edu.au

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damage and catch loss, reduction in catch rates and the need for increased fishing effort (Peterson et al. 2014). In areas where overfishing has caused stock declines, the frequency of interactions can increase, and economic losses may compound other social-economic costs, leading to retaliatory measures like intentional shooting or hunting, to protect fisher livelihoods (Gilman et al. 2006, Tixier et al. 2017). Spatial assessments of fisheries–dolphin interactions and understanding their social-economic and ecological impacts on fisheries and marine mammal species, respectively, can help to inform regional evidence-based conservation and management measures.

Along the west coast of India, Indian Ocean humpback dolphins *Sousa plumbea* (hereafter referred as humpback dolphins) occur in shallow inshore waters where several fisheries operate (~7000 fisher families; CMFRI 2012), including gillnet, cast net, purse-seine, shore-seine and trawl fisheries. In Ashtamudi estuary in Kerala, along the south-west coast of India, cast-net fishers and prey-herding humpback dolphins interact at the seawall, resulting in an increase in the catch of mullet *Mugil cephalus* for the cast-net fishers (Bijukumar & Smrithy 2012). More commonly, interactions are negative, whereby humpback dolphins extract fish and damage gillnets, shore seines and purse seines by targeting fish species such as mullet, pomfrets (*Pampus* spp.), Indian mackerel *Rastrelliger kanagurta* and sardines (*Sardinella* spp.). Such interactions have been documented in Sindhudurg, Maharashtra, where the fishing communities have a negative perception of humpback dolphins due to the considerable economic damage caused to their fisheries (Jog et al. 2018).

Stranding records of humpback dolphins list ~94 dolphin carcasses from Maharashtra and the neighbouring southern state of Goa between 2014 and 2022 (Marine Mammal Research and Conservation Network of India [MMRCNI], www.marinemammals.in, accessed on 9 October 2022), with 39 reports from Maharashtra only. Of these 39 carcasses, 19 exhibited evidence of interactions with fishing gear, such as garrotte wounds or lacerations on dorsal fins (MMRCNI). The limited data from necropsies and strandings in Maharashtra include 2 juveniles (~1–1.5 m total length), 6 calves (70–90 cm, with foetal folds) and 4 adults (>1.5 m) between 2019 and 2023. Necropsies conducted in Goa on 4 humpback dolphin carcasses between 2020 and 2021 also found remnants of ghost nets or pieces of fishing gear in the alimentary canal (MMRCNI). Despite these mortalities, management measures to mitigate fatal interactions are inadequate, at best. A behavioural, spatial and temporal assessment of interactions, specifically those with negative outcomes, and their impact on fisher livelihoods has the potential to inform management strategies.

Indian Ocean humpback dolphins are listed as 'Endangered' on the IUCN Red List of Threatened Species, with a declining population size in the species' range, from South Africa to the Bay of Bengal (Braulik et al. 2017). In India, these dolphins have a high protection status under Schedule I (Part I, Section 3C) of the Indian Wildlife Protection Act of 1972, which prohibits the intentional capture or killing of the species in Indian waters. The monitoring required to implement these laws is not in place, and marine mammal bycatch in remote areas is rarely documented. Fishers are aware of these laws and hence avoid reporting bycatch or bringing marine mammals onto a vessel or onshore, for fear of prosecution. Since 2018, the state government of Maharashtra has implemented a scheme offering a compensation of up to ~US$400 for the safe release of an entangled dolphin as a conservation measure (Marpakwar 2018). This approach, while useful, is not based on an assessment of the kind of fishing gear that places dolphins at risk, nor the types of fisheries most susceptible to economic losses due to interactions with dolphins.

The goal of our research is to fill this gap in knowledge. We assessed the potential risks to both dolphins and fisheries from their interactions along the Sindhudurg coastline, India, by (1) analysing the predominant group behaviours of dolphins in the absence and presence of different types of fishing vessels (actively fishing or travelling) and (2) mapping the spatial overlap of the distribution of humpback dolphins and different types of fishing vessels to delineate areas of high risk. We identify coastal fishing operations, by gear type and location, that pose risks to humpback dolphins in nearshore waters of Sindhudurg, and recommend future management and research priorities to inform a place-based conservation approach.

2. MATERIALS AND METHODS

2.1. Study area

The Sindhudurg coast in Maharashtra extends 120 km from Vijaydurg to Redi (Fig. 1a) on the west coast of India. The nearshore waters receive a large nutrient influx from 6 rivers that flow into the Arabian sea. There are 15 estuaries, spaced on average every ~5 km along this coastline (Kulkarni & Bhosale 2021).

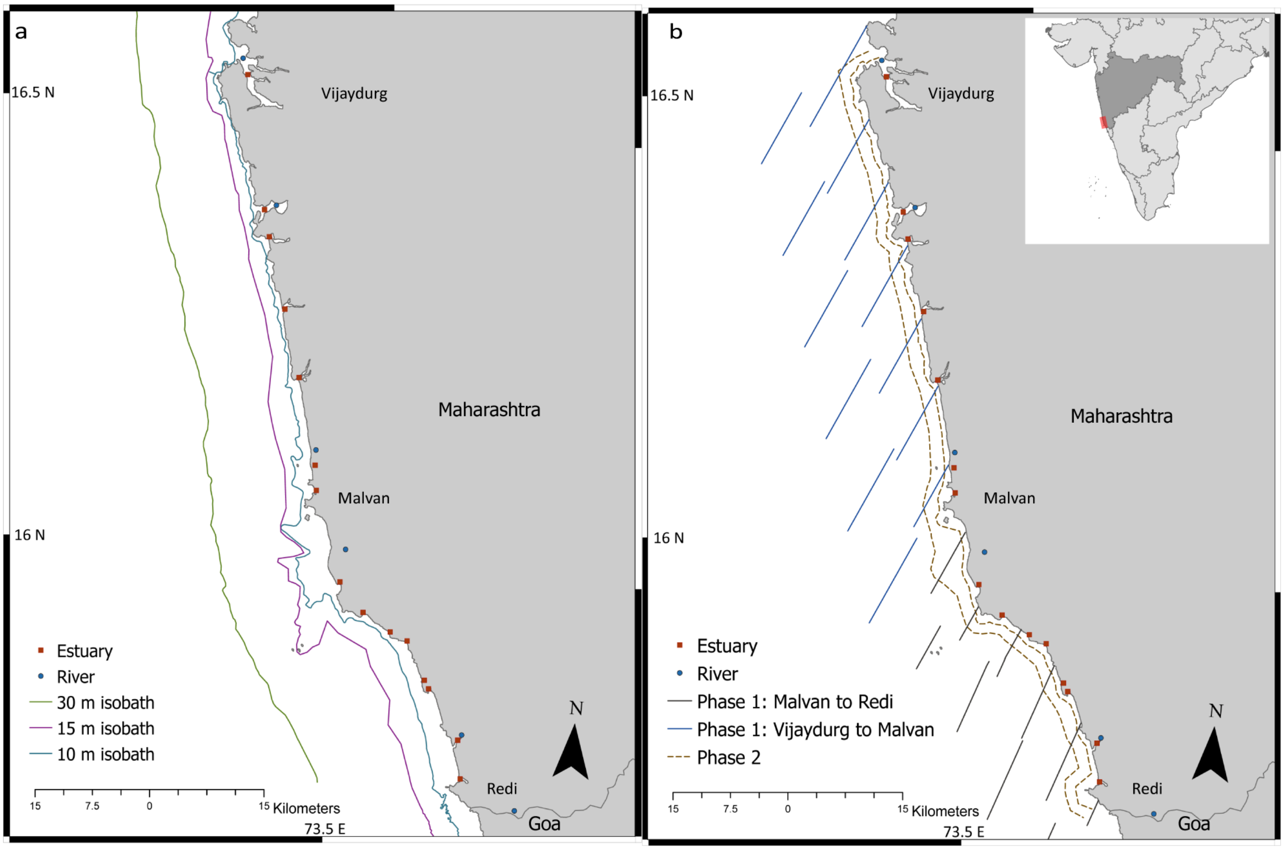

Fig. 1. (a) Study area. The Sindhudurg coastline is situated along the west coast of India, in the state of Maharashtra (dark grey, inset map). (b) In Phase 1, the transect lines were placed at a 45° angle to the coast (solid lines), initially restricted between Malvan and Redi (solid black lines) and later extended up to Vijaydurg (solid blue lines). In Phase 2, transect lines were placed parallel to the coast (brown dashed lines)

Fisheries in this region include commercial mechanized and non-mechanized operations using gillnets, trawlers, purse seines and shore seines, as well as subsistence fisheries using cast nets and gillnets. Vessel size ranges from about 5.5 to 14 m, depending upon the type of gear used for the operations. Gillnet vessels range between 5.5 and 11 m in length with outboard motors and mono- or multifilament gear with mesh sizes ranging from 0.5 to 38 cm. Purse-seine vessels are about 8.5 to 11 m in length, and trawl vessels range between 12 and 14 m in length. Fishery operations are multi-species and multi-gear, including a wide range of target species (Text S1 in the Supplement at www.int-res.com/articles/suppl/n053p035_supp.pdf) depending on season and availability of catch.

The Maharashtra Marine Fisheries Regulation Act of 1981 requires trawlers and purse-seine vessels to operate at least 12 nautical miles (~22 km) from shore. This area corresponds to the region beyond the 18 m depth contour (see Fig. 1a), specific to the Sindhudurg coastline, and is defined as the coastal zone (Pisolkar & Chaudhary 2016). Gillnet vessels can operate in any depth range within 22 km of the coastline. Shore seines generally operate within ~1 km from the shore. Seasonal fishing bans for trawler, purse-seine and offshore gillnet operations are implemented annually over 45–60 d between June and July, corresponding with the onset of the monsoon season.

2.2. Survey methodology

We conducted line transect surveys (Fig. 1b) in 2 phases: (1) in Phase 1, we assessed the occurrence, diversity and distribution of coastal cetacean species, i.e. dolphins, whales and porpoises; (2) in Phase 2, we specifically studied the common resident species, i.e. humpback dolphins, within 3 km of the shore.

We conducted the survey using a modified trawl vessel measuring 12 m in length and 3 m in width. Three experienced observes were stationed at the bow of the vessel (observer height on the vessel: 2.5 m) and conducted visual scans across a 180° field of view with binoculars (Nikon 7×50 Marine). One data logger recorded the data. The survey followed a standard strip transect search protocol during each survey phase with the vessel maintaining a constant speed of 11 km h^{-1} and a fixed heading. The transect lines in each phase were parallel, and the survey coverage extended to a width of 750 m on each side.

We conducted surveys in Phase 1 for a period of 5 mo (November 2012 to January 2013, May 2014 and November 2014). We placed survey lines at a 45° angle running from points 750 m out to 14 km from the coast, to assess the occurrence and diversity of coastal cetaceans across the gradient of depth and distance from shore (Fig. 1a). We restricted the study area between Malvan and Redi from November to January 2013 and May 2014, and it was extended up to Vijaydurg in the north in November 2014 (Fig. 1b).

During Phase 2 (November–December 2014, January 2015, March–May 2015), we placed 2 survey lines parallel to the coast at distances of 750 m and 2.25 km from the shore. These distances were within the range of humpback dolphin distribution observed during Phase 1. The changes were implemented to achieve 2 goals: (1) optimize the survey effort along the coastal stretch, considering funding constraints, and (2) maximize the chances of collecting data specifically on humpback dolphin ecology and initiate photographic mark–recapture studies.

We collected data with an aim of mapping the space use of humpback dolphins, and the distribution and activity of fishing vessel traffic during dolphin sightings. We recorded the number of groups of humpback dolphins sighted, predominant group behaviour and the presence and activity of fishing vessels within a 500 m radius from the dolphin sighting. We used these data to: (1) explore the differences in the predominant group behaviour of dolphins in the presence (active and travelling) and absence of different fishing vessel types, and (2) map the spatial distribution of dolphin groups and different fishing vessels, to understand the spatial overlap between dolphins and fisheries, assess which fisheries pose potential risks to the dolphins (Chilvers & Corkeron 2001, Chilvers et al. 2003, Mann et al. 2007) and delineate potential areas of high risk within dolphin habitat.

2.2.1. Observations of dolphin groups and predominant group behaviour

For each dolphin group encountered on a transect during Phases 1 and 2, we recorded the time, sighting location and depth at the location using an on-board depth sounder with a through-hull transducer (Garmin GPSMAP 585S). Distance from shore for each dolphin sighting was then derived post hoc, manually, from the GPS location of each sighting on navigation charts (BlueChart for India) using the Garmin HomePort software. After recording these data, we focused survey effort on approaching the group of animals to collect data on group size and predominant group behaviour.

We defined groups as individuals engaged in the same behavioural activity, with approximately < 10 m distance among individuals (Smolker et al. 1992). At each group encounter, we recorded the minimum, maximum and 'best' group size estimates (Baird et al. 2003). 'Best' group size estimates (the mean of 3 independent observer estimates logged by consulting each observer separately) were used for further data analysis. Encounter rates were calculated for the total survey effort (total time and distance covered) and survey effort over summer and winter seasons, for Phases 1 and 2.

The predominant group behaviour was assessed using scan sampling within the first 5 min after the groups were sighted (Shane 1990). The analyses used predominant group behavioural states classified into 5 categories: foraging, foraging + socialising, socialising, travelling and milling (adapted from Karczmarski et al. 1997).

2.2.2. Observations of fishing vessels

In Phase 1, we recorded fishing vessels only when they were within a 500 m radius of a cetacean sighting. However, in Phase 2, we recorded the presence and activity of any fishing vessel encountered within approximately 750 m on either side of the survey vessel as well as during dolphin sightings.

We collected information on (1) type of fishing vessel (gillnet, purse seine, shore seine, trawler), (2) activity of the fishing vessel (active, i.e. fishing; or inactive, i.e. travelling) and (3) number of fishing vessels of each type.

We identified the type and activity of fishing vessels based on visual observations. 'Active' vessels were engaged in a fishing operation, usually when vessels were stationary (gillnet and purse-seine vessels) or travelling at a very slow speed (trawl vessels) with gear deployed (discerned with the help of marker buoys on the gear). Travelling fishing vessels were defined as vessels observed to move at a relatively faster speed than when the vessels were engaged in fishing, with no gear deployment. Travelling vessels were included in the data analysis as present but inactive.

2.3. Data analysis

2.3.1. Difference in dolphin group behaviour in the presence and absence of fishing vessels

We used Pearson's chi-squared test with Yate's continuity correction to compare the proportions of predominant dolphin group behaviour with the presence, type and activity of fishing vessels observed in Phases 1 and 2. First, we compared the proportions of the 5 main dolphin behavioural states: foraging, foraging + socialising, socialising, travelling and milling, separately with the presence or absence of fishing vessels. To increase the sample sizes, we combined (1) the 2 foraging-related behavioural states, i.e. foraging, and foraging + socialising, into a single behavioural state called 'foraging behaviours', and (2) socialising, travelling and milling, into a new category termed 'other behaviours'.

We used a generalized linear model with binomial distribution to test the relationship between the presence and absence of dolphin groups engaged in foraging behaviours (response variable) and the predictor variables: (1) time of day; habitat parameters: (2) depth and (3) distance from shore; (4) dolphin group size; and (5) total number of fishing vessels (active and inactive), using the software R version 4.2.2. (R Core Team 2022). Given the small sample size, this approach allowed us to efficiently explore the combined influence of these factors on dolphin behaviour accounting for potential interactions among predictor variables.

2.3.2. Spatial mapping of humpback dolphins and fishing vessels

We used humpback dolphin and fishing vessel observations only from the Phase 2 surveys for spatial mapping, using ArcGIS Pro Version 2.8 (Esri), because fishing vessel observations were not recorded in the presence and absence of dolphin sightings during Phase 1.

We first created a polygon buffer of 750 m (corresponding to the width of each strip transect in Phase 2, and the field of view of the 3 observers on the survey vessel, i.e. ~180°) along the parallel transect lines. We then divided this polygon into cells of approximately equal area using the 'Subdivide Polygon' tool and manual editing, resulting in 42 cells of relatively equal areas (mean: 7.93 km^2; range: 6.5–9.4 km^2; total area: 333.05 km^2). We calculated (1) dolphin sighting density and (2) fishing vessel (active and travelling) density, for each cell, by dividing (1) the total number of dolphin individuals and (2) the number of fishing vessels of each type recorded, in that cell by its area (km^2). These densities were binned into 3 classes (none, low and high) based on the natural breaks (Jenks) function. We measured the number of cells and the area of each cell where dolphins and different fishing vessel types occurred. The spatial distribution of dolphins and fishing vessels of different types was then illustrated as a percentage of the total Phase 2 survey area (i.e. 42 cells). The overlap between the cells where dolphins and fishing vessels of different types occurred was measured relative to the dolphin habitat (21 cells) and mapped (see Fig. 3a–f). We then created a risk matrix based on the intersections of different densities of dolphins and fishing vessels, to delineate areas of high, moderate and low risk (see Table 5a), in the context of humpback dolphin habitat. We did not consider shore seines in the spatial analyses, since the number of observations was low (5 vessels).

2.3.3. Study limitations

Survey effort was unequal over time and space due to funding and logistical constraints. Dolphin behavioural observations were restricted to recording the predominant group behaviours. We did not measure the changes in group size or behaviour with fishing vessel presence or activity.

All transect surveys were within 14 km of the coast and only during daylight hours. Fishing activity in this region is mainly conducted either at dawn or dusk, depending on local tide timings spanning areas farther than 14 km. Therefore, distribution of fisheries and the diel patterns of dolphin space-use and fishing activity are not comprehensively represented.

3. RESULTS

We conducted line transect surveys in Phases 1 and 2, combined, for over 510.40 h and across 5079 km (Table 1). These surveys spanned water depths between 2.6 and 26.4 m (mean: 9.4 m, median: 9.2 m, Q1[25%]: 7.8 m, Q3[75%]: 11 m), and distances of 0.09 to 6.7 km from shore (mean: 0.71, Q1: 0.52 km, Q3: 1.12 km). We encountered 4 species of cetaceans: Indo-Pacific finless porpoise *Neophocaena phocaenoides* (40 sightings), Bryde's whale *Balaenoptera edeni* (5 sightings), blue whale *B. musculus* (1 sighting) and humpback dolphin (175 sightings). We illustrate further results for humpback dolphin sightings only.

Table 1. Sampling coverage, sample sizes and encounter rates for humpback dolphins during line transect surveys. Total survey effort during both Phases 1 and 2 of this study was 510.40 h over 5079 km

Sampling coverage	Phase 1: 45° transects	Phase 2: Parallel transects
Total duration	November 2012 to January 2013; May 2014, and November 2014	November–December 2014, January 2015; March–May 2015
Time (h)	172.65	335.75
Distance (km)	1134	3745
Number of dolphin sightings	49	126
Sightings per hour	0.30	0.38
Sightings per km	0.04	0.05
Sightings per 100 km	3.8	4.73
Group size range; median	1–50; 4	1–120; 8

3.1. Observations of dolphin groups and predominant group behaviour

Of the 175 groups of humpback dolphins, we observed 49 groups in Phase 1 and 126 groups in Phase 2. Encounter rates were 3.8 and 4.7 groups per 100 km, and 0.30 and 0.38 groups per hour, for survey Phases 1 and 2, respectively (Table 1). Maximum sightings were in locations with water depths between 8 and 11 m (47%; 83 sightings), and between 0.5 and 1 km from shore (48%; 84 sightings).

Group sizes varied from 1 to 120 dolphins (median: 6), across both survey phases. In Phase 1, the groups sizes ranged between 1 and 50 (median: 4), and in Phase 2, between 1 and 120 dolphins (median: 8).

Of the 6 predominant group behavioural states recorded during both Phases 1 and 2, foraging was most frequently observed (50 groups), followed by travelling (37) and socialising (32). Foraging + socialising groups had the highest group sizes (range: 3–120; median: 30), followed by foraging (range: 1–56, median: 5) and socialising (range: 2–45, median: 8) (Table 2).

Foraging + socialising groups had relatively high group sizes in the presence (range: 3–110; median: 30) and absence (range: 10–120; median: 28.5) of fishing vessels, compared with other behavioural states (Table 2).

Table 2. Description of observed behavioural states and their associated statistics, collected during line transect surveys for the total number of groups observed in each behavioural state and for the number of groups observed in the absence and presence of fishing vessels of all types (gillnet, trawl, purse-seine and shore-seine vessels)

Behaviour	Description	Number of groups observed (percentage out of total number of observations) [group size (median; range)]		
		Total	In the absence of fishing vessels	In the presence of fishing vessels
Foraging behaviours				
Foraging	Variable directional movement with raised tail flukes, deep dives, rapid directional dives (chases) and side dives	50 (28.6%) (5; 1–56)	19 (38%) (4; 2–35)	31 (62%) (6; 1–56)
Foraging + socialising	Individuals engaged in both foraging and socialising behaviours and showing rapid interchangeability between these behaviours at varied time intervals, with higher percentage of foraging behaviour	25 (14.3%) (30; 1–120)	8 (32%) (28.5; 10–120)	17 (68%) (30; 3–110)
Other behaviours				
Socialising	Bodily contact and surface activity including tail slaps, breaching, surface splashing, rubbing, rake marking, belly-up swimming, sexual displays and mating	32 (18.3%) (8; 2–45)	24 (75%) (8; 2–35)	8 (25%) (20; 5–50)
Travelling	Uniform parallel directional movement with rhythmic bouts of resurfacing	37 (21.1%) (3; 1–35)	29 (78.4%) (2; 1–35)	8 (21.6%) (5; 1–20)
Milling	Variable surfacing and swimming activity, usually characterized by a change in directionality among individuals in a group but stationary over an area	31 (17.7%) (5; 1–30)	23 (74.2%) (6; 1–15)	8 (25.8%) (3; 1–30)

3.2. Observations of fishing vessels

We observed a total of 207 fishing vessels during dolphin sightings; of these, 20% were observed in Phase 1 and 80% in Phase 2 (Table 3). Gillnets accounted for 55% of the total fishing vessels observed during both Phases 1 and 2 and only during dolphin sightings, followed by trawl (32%), purse-seine (11%) and shore-seine (2%) vessels (Table 3a). We observed purse-seine vessels only during Phase 2 surveys (2014–2015). Across both Phases 1 and 2, we observed active and travelling gillnet vessels between 2.7 and 14.3 m water depths (mean: 15.2 m), and between 0.27 and 1.51 km from the shore (mean: 1.79 km), during dolphin sightings.

We also observed trawl and purse-seine vessels in shallow waters, i.e. in areas where these fishing gears are not allowed to operate. Trawl vessels occurred between 3.2 and 17.4 m water depths, and 0.32 and 2.89 km from shore (mean: 1.03 km). Active trawl vessels (52 vessels) were observed between 5.6 and 17.4 m depth (mean: 11.25 m), and 0.33 and 2.89 km from the shore (mean: 1.27 km).

We observed purse-seine vessels (n = 38 vessels) between 6.2 and 13.5 m depth and between 0.11 and 0.99 km from shore. Active purse-seine vessels (13) occurred between 10 and 13.5 m water depth (mean: 12.4 m) and between 0.36 and 0.99 km (mean: 0.6 km) from the shore.

Table 3. Percentage of different fishing vessel types observed during surveys. (a) Percentage of fishing vessels observed across survey Phases 1 and 2 only in the presence of dolphin sightings; (b) percentage of active and inactive (travelling) fishing vessels across both Phases 1 and 2 only in the presence of dolphin sightings; (c) percentage of fishing vessels observed only in Phase 2 in the presence and absence of dolphin sightings

Survey phase	Gillnet	Trawl	Purse seine	Shore seine
(a) Vessels observed in the presence of dolphins				
Phase 1	9	10	0	1
Phase 2	46	22	11	1
Overall	55	32	11	2
(b) Vessel activity in the presence of dolphins in Phases 1 and 2				
Active	42	25	6	1
Inactive	13	7	4	0
(c) Vessels observed in Phase 2				
Overall	38	43	19	1
Presence of dolphins	6	3	3	0
Absence of dolphins	32	40	16	1

In Phase 2, trawl vessels were more common, both in the presence and absence of dolphin sightings (43%), followed by gillnet vessels (38%), purse seines (19%) and shore seines (1%) (Table 3c).

3.3. Differences in dolphin group behaviour in the presence and absence of fishing vessels

The number of groups engaged in foraging behaviours (foraging + socialising, and foraging) (44%) was higher in the presence of fishing vessels (χ^2 = 28.706, df = 4, $p < 0.0001$) than in their absence (Fig. 2). This association was also significant when the fishing vessels were active (χ^2 = 4.286, df = 1, p = 0.043). The likelihood of dolphins being engaged in foraging behaviours increased with the presence of gillnet fishing vessels (χ^2 =

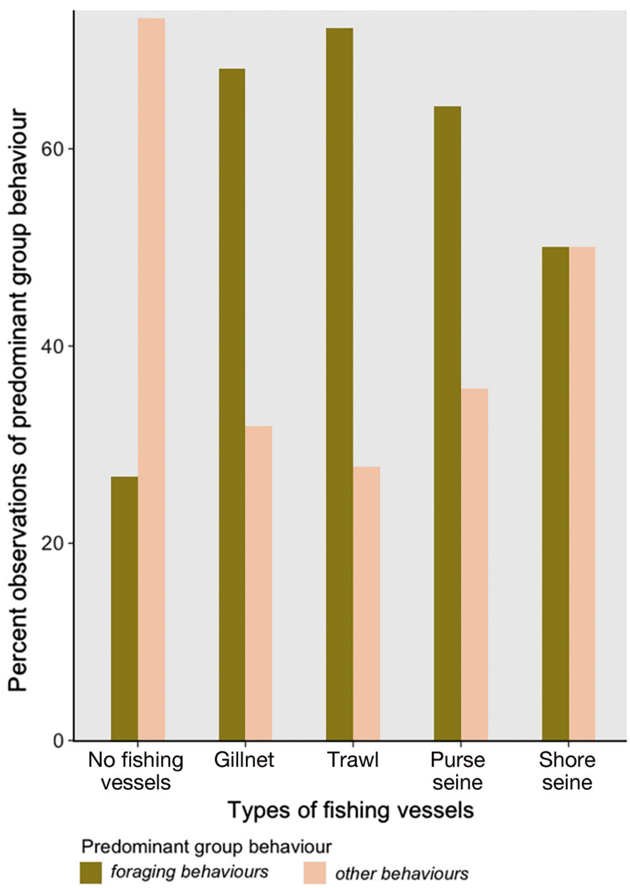

Fig. 2. Proportions of predominant dolphin group behaviours in the presence and absence of different types of fishing vessels (gillnet, trawl, purse seine and shore seine). The 2 behavioural states foraging and foraging + socialising are combined into a single behavioural state, 'foraging behaviours'. The category 'other behaviours' includes socialising, travelling and milling

15.621, df = 1, $p < 0.0001$) (Fig. S1a), and when the gillnet vessels were actively fishing (χ^2 = 10.445, df = 1, p = 0.001) (Fig. S1b). While the likelihood of foraging behaviours also slightly increased in the presence of trawl vessels (χ^2 = 5.902, df = 1, p = 0.015) (Fig. S1c), whether the trawlers were actively fishing or travelling did not affect dolphin behaviours (χ^2 = 3.136, df = 1, p = 0.077) (Fig. S1d). The likelihood of foraging behaviours was not significantly associated with the presence (χ^2 = 2.117, df = 1, p = 0.145) or activity (χ^2 = 1.446, df = 1, p = 0.229) of purse-seine vessels.

We tested the significance of the predictor variables (1) time of day; habitat parameters: (2) depth and (3) distance from shore; (4) dolphin group size; and (5) total number of fishing vessels on the presence and absence of dolphin groups engaged in foraging behaviours (response variable) (Table 4). Larger groups (>~10 individuals) of dolphins were more likely to be engaged in foraging behaviours (n = 75 groups of dolphins) than smaller groups. The likelihood of the presence of groups engaged in foraging behaviours decreased slightly with the time of day from 07:00 to 14:00 h and increased significantly with an increase in the number of fishing vessels present (of all types and activities). Depth and distance from shore showed no association with groups engaged in foraging behaviours.

Of the 175 dolphin groups sighted, a higher percentage of groups were engaged in socialising (75%), travelling (78.4%) and milling (74.2%) when there were no fishing vessels around (Fig. 2).

3.4. Spatial overlap between dolphins and fishing vessels

Dolphins occurred in 21 (50%) of the 42 cells (~164 km^2) of the survey area in Phase 2 (low dolphin density: 33%, high dolphin density: 17%) (Fig. 3a, Table 5). Gillnet vessels occurred in 36 cells (86%) and 284 km^2; trawl vessels in 39 cells (93%) and 310 km^2 and purse-seine vessels in 34 cells (81%) and 268 km^2 of the total survey area. Overall, a combination of any 2 or all 3 types of fishing vessels occurred in every cell across the entire study area (100%), indicating that the entire survey area was subject to fishing activity. Areas with high densities of dolphins and fishing vessels (gillnet, trawl and purse seine) occurred close to the shore (<~750 m) and near estuaries (Fig. 3—e).

Gillnet vessels had a 95% overlap with dolphin habitat across the study area, while trawl and purse-seine vessels each had an 86% overlap. The high-density dolphin habitats had a complete overlap with gillnet and trawl fisheries (100% each, Table 5), while purse seines overlapped 75% with high-density dolphin areas. Altogether, gillnet, trawl and purse-seine vessels had a 100% overlap within both high- and low-density dolphin habitats.

We identified 8 key areas of high risk within the study site, located near the shore (<~750 m) and around 7 estuaries (Fig. 3f). Notably, 2 clusters of these high-risk areas were observed within 500 m of the shore, adjacent to estuaries, in the central (3 cells) and southern regions (2 cells). Four of these cells coincided with areas of high-density dolphin habitats.

Table 4. Parameter estimates for the generalized linear model, presented as probabilities relative to the response variable (*a*), i.e. the presence or absence of dolphin groups engaged in foraging behaviours, with respect to the following explanatory variables: (*i*) time of day; habitat parameters: (*ii*) depth and (*iii*) distance from shore; (*iv*) dolphin group size; and (*v*) total number of fishing vessels (active and inactive). The corresponding GLM equation is: $a \sim i + ii + iii + iv + v$. *p < 0.05

Variable in GLM equation		Estimate	SE	*z*	Pr(>|*z*|)
Response variable					
a	Presence/absence of groups engaged in foraging behaviours (N = 75 groups)	−0.95	0.92	−1.04	0.30
Explanatory variables					
i	Time of day	−0.27	0.14	−1.93	0.05
ii	Depth	0.05	0.08	0.67	0.50
iii	Distance from shore	0.03	0.50	0.06	0.95
iv	Dolphin group size	0.04	0.02	2.52	0.01*
v	Total number of fishing vessels	0.33	0.13	2.54	0.01*

Hosmer and Lemeshow goodness of fit (GOF) test, χ^2 = 1.666, df = 4, p = 0.796

4. DISCUSSION

Our study (2012—2015) provides insights into the influence of fishing vessels on humpback dolphin space use and foraging behaviour, with implications for management and conservation strategies, as well as future research priorities in the Sindhudurg region regarding marine mammal and fisheries interactions.

The Sindhudurg coastal region is an ecologically and economically critical area (Pisolkar & Chaudhary 2016), with the nearshore coastal areas harbouring a diversity of marine mammals and fisheries. The resident population of humpback dolphins in the Sindhudurg coastal district is distributed along the

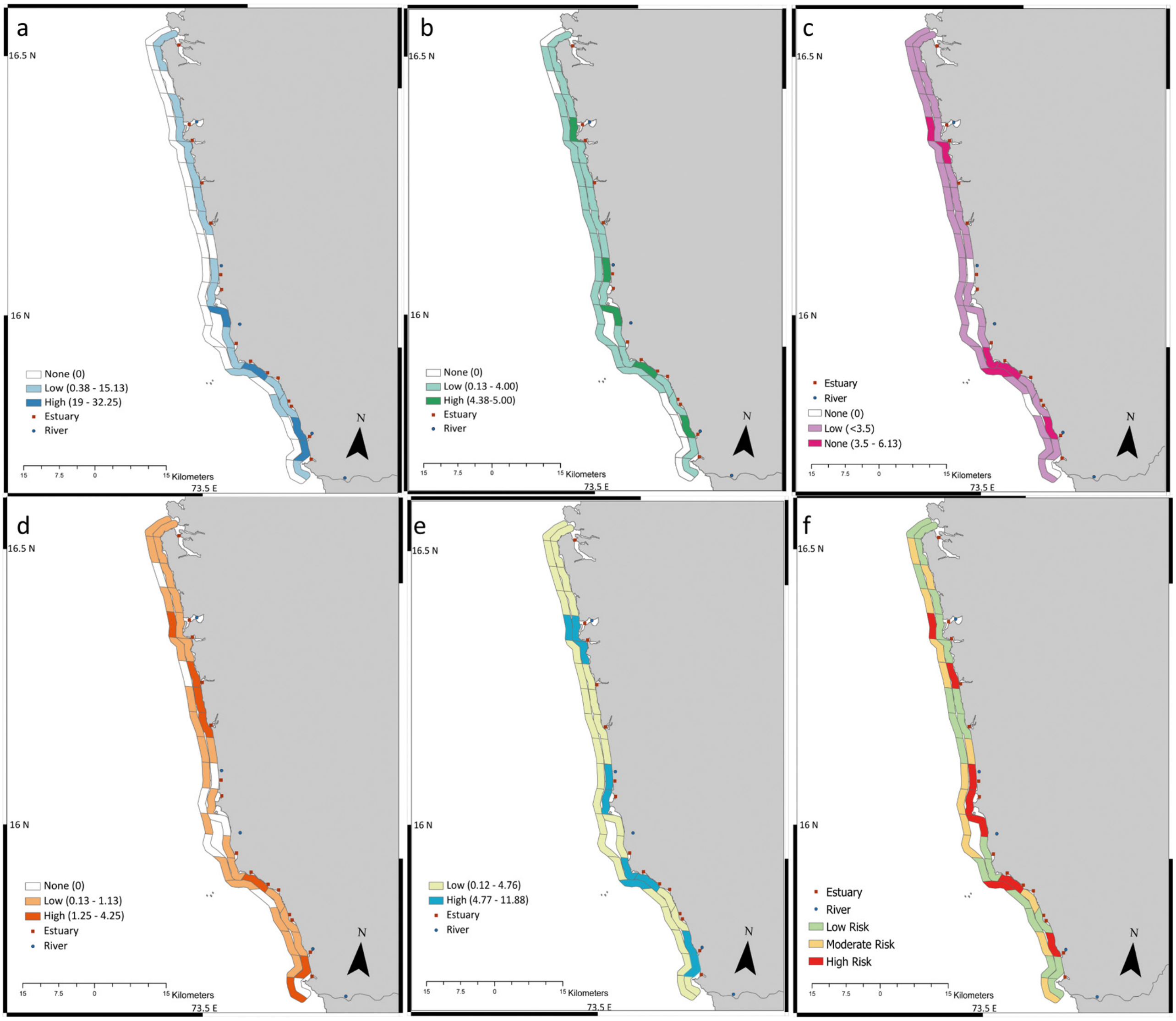

Fig. 3. Humpback dolphins and fishing vessel distributions observed during transect surveys of Phase 2. (a) Humpback dolphin density (ind. km^{-2}), (b) gillnet vessel density (n vessels km^{-2}), (c) trawl vessel density (n vessels km^{-2}), (d) purse-seine vessel density (n vessels km^{-2}), (e) all types of fishing vessels (n vessels km^{-2}), and (f) low-, moderate- and high-risk areas based on the distribution of dolphins and all types of fishing vessels

coast within ~750 m and showed a high frequency of foraging behaviours in this area. The median group sizes observed across both survey phases (1 and 2) were fairly small: 4 and 8, respectively. The presence of several estuaries and a relatively uniform distribution of fish such as sardines and mackerel (Liu et al. 2020, 2021) in this region probably influence this distribution of dolphins and the distribution of gillnet, trawl and purse-seine fisheries. This study emphasizes the spatial overlap between dolphins and fisheries in nearshore waters.

These distribution patterns also provide insights into the possible influences of fisheries on dolphin behaviour in this region. Larger dolphin groups were observed more likely to engage in foraging behaviours around fishing gears. The presence of fishing activity could possibly increase each individual's access to prey (Silva et al. 2010). Habitat parameters such as depth and distance from shore were not associated with the likelihood of dolphin foraging behaviours, suggesting that the presence of fishing vessels may have a stronger influence on dolphin foraging behaviours than these environmental parameters.

This spatial overlap could provide short-term benefits for marine mammals, creating new foraging opportunities directly facilitated by fishing opera-

Table 5. Risk matrix representing spatial overlap between dolphins and fishing vessels: (a) low-, moderate- and high-risk areas, depending on the intersection of different densities of dolphins and fishing vessels in each cell. The survey area extended over 333 km^2. Dolphins occurred over 164 km^2. The values in the table represent the percentage of cells with different dolphin and fishing vessel densities overlapping in different areas of risk: (b) Gillnet vessels (~284 km^2); (c) trawl vessels (~310 km^2), (d) purse-seine vessels (~268 km^2), (e) all fishing vessel types (~333 km^2)

	Dolphin density (dolphins km^{-2})		
	None (0)	Low (< 15.13)	High (15.13–32.25)
(a) Fishing vessel density (vessels km^{-2})			
None	Low risk	Low risk	Low risk
Low	Low risk	Moderate risk	Moderate risk
High	Low risk	High risk	High risk
	None (168 km^2)	Low (132 km^2)	High (33 km^2)
(b) Gillnet vessel density (vessels km^{-2})			
None (0) (49 km^2)	24 %	6 %	0 %
Low (< 4) (243 km^2)	76 %	82 %	25 %
High (4–5) (41 km^2)	0 %	12 %	75 %
(c) Trawl vessel density (vessels km^{-2})			
None (0) (23 km^2)	0 %	18 %	0 %
Low (< 3.5) (255 km^2)	67 %	65 %	50 %
High (3.5–6.13) (55 km^2)	33%	18 %	50 %
(d) Purse-seine vessel density (vessels km^{-2})			
None (0) (65 km^2)	24 %	12 %	25 %
Low (< 1.13) (228 km^2)	67 %	82 %	25 %
High (1.13–4.25) (40 km^2)	9 %	6 %	50 %
(e) All fishing vessel density (vessels km^{-2})			
None (0)	0 %	0 %	0 %
Low (< 4.76) (104 km^2)	76 %	59 %	75 %
High (4.76–11.88) (229 km^2)	24 %	41 %	25 %

tions (Esteban et al. 2016, Tixier et al. 2020). Calves or juveniles might be more affected by such foraging opportunities, due to the vertical transmission of foraging techniques from mother to offspring (Meulman et al. 2013). Over the long term, behavioural habituation to feeding in association with fishing activities can result in permanent changes in social structure of dolphin communities (Shane et al. 1986) compounding the risks from spatial overlap of dolphins with fisheries. Previous research suggests that dolphins, habituated to foraging associated with fishing gear, tend to concentrate around such fishing activities (Cunningham-Smith et al. 2006, Finn et al. 2008), reducing their home ranges, which are also dependent on prey locations (Ballance 1992). Increased instances of fisheries-associated foraging behaviours and related risks of gear ingestion and entanglement can also rapidly impact dolphin communities (Powell & Wells 2011).

The spatial analyses in this study advance our current knowledge of fisheries space use and management. Gillnet fisheries are of particular concern in dolphin habitats given their marginally higher percentage of overlap with dolphins, compared with trawl and purse-seine fisheries. The fact that 3 key high-risk areas in the central and southern part of the study area correspond with areas of high dolphin densities also emphasizes the potential risks, from gillnet fisheries in particular. These results are especially pertinent in light of previous research highlighting substantial concerns surrounding gillnet interactions with marine mammals, such as unintentional entanglements and injuries (Read et al. 2006). Moreover, considering the proximity of these high-risk areas to estuaries, it is highly probable that the co-occurrence and reliance of both gillnet fisheries and dolphins on these productive fishing grounds contribute to the overlap. While this result confirms previous evidence of interactions between gillnet fisheries and humpback dolphins (Jog et al. 2018), we demonstrate that the central and southern regions are of particular concern due to the increased likelihood of adverse social ecological consequences of interactions with dolphins, i.e. gear damage and catch loss (Table 6).

The non-compliance of trawl and purse-seine fisheries with mandated area bans could also increase this risk. Studies have documented the adverse impacts of trawl and purse-seine fisheries in this region leading to biodiversity loss, habitat destruction, resource competition among different fisheries (Lakra et al. 2021) and a decline in fish diversity and abundance (Singh et al. 2010). This resource depletion could lead to an increased likelihood of spatial overlap of dolphins with trawl and purse-seine fisheries and the associated risks of adverse interactions (Klein et al. 2010).

This study provides insights directly relevant to the conservation management of dolphins in the Sindhudurg region: (1) The coastal area within 1 km of the shore is an important dolphin habitat. High densities of dolphins and fisheries co-occur in this habitat. Although gillnet vessels pose a high risk to dolphins in the near coastal habitat, trawl and purse-seine

Table 6: Risk assessment based on the spatial overlap between dolphins and fishing vessels. We used the risk matrix from Table 5a to list the probable consequences of this overlap for both fishing communities (dolphin depredation of fishing gear and economic damage) and dolphin populations (entanglement/injury risk). The corresponding management recommendations are based on these consequences. NA: not applicable

Risk categories	Probable consequences: Social-economic	Probable consequences: Ecological	Research priorities	Management suggestions
Low	NA	NA	Monitoring dolphin populations	Continue monitoring efforts as required
Moderate	Gear damage[a] Catch loss[a]	Unintended entanglements in fishing gear, injuries, mortalities	Monitoring strandings, mortalities to ascertain cause of death (gear ingestion, entanglements in gear, etc.)	Spatial management: re-assessing current fishery management for compliance with existing area fishing bans in dolphin habitats
High	Resource competition among different fisheries and with dolphins[b]	Resource competition with fisheries[b]	Assessing social-economic impacts of interactions on fisheries; monitoring of fishing activity for non-compliance with existing area fishing bans within dolphin habitat	Mitigation of interactions: monetary compensation to offset costs of gear damage

[a]Dolphin—fishery interactions
[b]Fisheries non-compliance with area fishing bans

vessels could also have adverse impacts on coastal marine wildlife. (2) There is a high degree of overlap of dolphin habitat with gillnet fisheries followed by trawl and purse-seine fisheries, particularly in 8 key high-risk areas near estuaries. Our risk assessments for these areas in the central and southern regions can serve as a baseline for understanding and identifying priority habitats in the near coastal zone along the Sindhudurg coast (Ross et al. 2011). (3) Trawl and purse-seine fisheries do not comply with mandated area bans particularly within dolphin habitat. The spatial analyses therefore also indicate a need to assess the efficacy of current fishery management strategies in addition to better understanding the interactions between fisheries and humpback dolphins.

If fishery livelihoods are affected by inadequate fishery management, a top-down approach to spatial management to mitigate interactions is likely counterproductive (Mendoza-Portillo et al. 2020, MacKeracher et al. 2021). Understanding the inadequacies of fisheries management through the lens of dolphin—fisheries interactions identifies some of the challenges impeding successful interaction mitigation strategies (Jog et al. 2022). This perspective points towards a potential underlying issue of resource depletion possibly stemming from overfishing, leading to the non-compliance of trawl and purse-seine fisheries with area bans. However, there could be other social-economic causes that necessitate further investigation of fisheries non-compliance in the region.

Rather than a general top-down approach, we suggest the desirability of developing of a place-based management approach, i.e. a participatory network of local fishers, researchers and managers to create an information exchange among fishers and managers, facilitated by researchers. This network can be mobilized to monitor interactions as well as fishing practices, with the help of key informants, i.e. respected, local fishers who have experience operating different gear types. This dialogue could help managers to (1) prioritize evidence-based evaluations of current fisheries management strategies, for example, fisheries non-compliance with mandated area bans, with more focus on the high-risk areas in dolphin habitats; (2) assess the social and economic impacts of interactions with dolphins, i.e. estimate the cost of gear damage and catch loss for different fishing gears due to interactions with dolphins. These assessments can also be used to inform interaction mitigation strategies, such as monetary compensation to fishers to at least offset the cost of gear damage; (3) monitor humpback dolphin and other marine mammal strandings to understand cause of death due to entanglements in fishing gear; and (4) facilitate an adaptive management response to mitigate interactions (bycatch and depredation) based on the knowledge and perspective of fishers with an emphasis on high- and moderate-risk areas identified in this study (Table 6).

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