Received: 27 September 2019 | Revised: 21 March 2021 | Accepted: 27 May 2021
DOI: 10.1002/aqc.3658

RESEARCH ARTICLE

WILEY

Fisheries induced shift in sea snake community assemblages along the Konkan coast, India

Chetan Rao[1] | Shawn Dsouza[1] | Trisha Gupta[1] | Muralidharan Manoharakrishnan[1] | Aaron Savio Lobo[2]

[1]Biodiversity and Resource Monitoring Program, Dakshin Foundation, Bengaluru, Karnataka, India

[2]Independent Consultant, Salvador Do Mundo, Goa, India

Correspondence
Chetan Rao, Biodiversity and Resource Monitoring Program, Dakshin Foundation, #1818, 5th Main, Sahakar Nagar 'C' block, Bengaluru 560092, Karnataka, India.
Email: chetan.rao@dakshin.org

Abstract

1. The impacts of fisheries on several charismatic marine fauna have been a subject of global concern. Sea snakes share the same habitats as many commercially important fish species and often end up as fisheries bycatch.
2. Previous studies of bycatch from India have been limited to individual reports of mortality, with little information on the regional community structure of sea snakes. This study was carried out along the Konkan coast, off the central west coast of India, between 2016 and 2018, to determine trends in the bycatch of sea snakes in coastal fisheries.
3. In this study, 922 sea snakes were encountered in 916.57 gillnet haul hours and 449.16 trawlers haul hours of fishing, comprising largely of two species: beaked sea snake (*Hydrophis schistosus*) and spine-bellied sea snake (*Hydrophis curtus)* (83.05 and 16.94% respectively) which was in stark contrast to a similar study conducted in 2002–03, which recorded a dominance of *H. curtus* (84%) followed by *H. schistosus* (14%) in the same region. Both studies, however, indicated higher mortality in *H. curtus* than in *H. schistosus* in trawl nets.
4. This study highlights the significant impact of non-selective fishing practices on regional assemblages of other marine organisms such as sea snakes from South Asia, which has been relatively understudied, and the potential consequences for local ecosystems.

KEYWORDS
beaked sea snake, bycatch, fisheries, *Hydrophis curtus*, *Hydrophis schistosus*, Konkan coast, mortality, spine-bellied sea snake, trawling

1 | INTRODUCTION

Industrial fishing practices are known to be unsustainable and have negative impacts on target and bycatch species, resulting in degraded ecosystems (Gray, 1997; Jackson et al., 2001). Practices such as trawling are highly unselective and large quantities of non-target species are hauled in the nets as bycatch (catch with limited or no commercial value; Alverson et al., 1994; McConnaughey et al., 2019). A variety of marine species around the globe including charismatic megafauna such as cetaceans, sea birds, sea turtles and sea snakes (Hall, Alverson & Metuzals, 2000; Lewison et al., 2014) are threatened in the process. Although each faunal group responds differently to fishing pressures owing to life history patterns, large-scale uncontrolled mortality owing to fishing continues to be a threat to sustained population recovery for many marine species (Stevens et al., 2000; Milton, 2001).

Sea snakes are a lineage of venomous snakes (Family: Elapidae) which originated in Australia around 6–8 million years ago

(Sanders et al., 2013). They are the most diverse group of marine reptiles with over 60 species reported and occupy a wide range of habitats such as mud flats, coral reefs, seagrass beds and estuaries (Sanders et al., 2013; Udyawer et al., 2018). They are mid-trophic-level predators and a majority of the species are specialized benthic predators (Voris & Voris, 1983) playing a vital ecological role in coastal and reef ecosystems (Voris, 1972; Ineich et al., 2007). All but one sea snake species exhibit *k*-selected life history traits, such as low fecundity, slow population growth and late attainment of sexual maturity (around 2 years), making them particularly vulnerable to anthropogenic impacts (Lemen & Voris, 1981; Wassenberg et al., 1994; Pears et al., 2012). According to Lemen & Voris (1981), the beaked sea snake (*Hydrophis schistosus*; then *Enhydrina schistosa*) exhibits an R-type life history strategy as compared with other species, with a higher fecundity (17.8 clutch size on average as compared with 3.3–6 clutch sizes in other species such as the spine-bellied sea snake; *Hydrophis curtus* – then *Lapemis curtus*) and early sexual maturity, thus making it easier for it to expand its territory and range into vacant niches.

Although frequently encountered in fishing nets, data on the current status and responses of sea snakes to fishing pressures are scarce; data on mortality and thorough vulnerability assessments are also severely lacking (Tu, 1974; Udyawer et al., 2018). According to Wassenberg, Milton & Burridge (2001), bycatch mortality rates in sea snakes can be as high as 48.5% from trawl fisheries in Northern and Eastern Australia between August and November 1998. Countries such as Vietnam, Thailand, Philippines and Australia also harvest sea snakes for meat, medicines and leather (Wassenberg et al., 1994; Heatwole, 1997; Milton, 2001; Wassenberg, Milton & Burridge, 2001; Van Cao et al., 2014). However, decline in harvests has been observed in these areas. e.g. harvest figures show a 30% decline in sea snake-catch from the Gulf of Thailand from >12 tonnes caught in 2009 to ∼8.5 tonnes in 2013 (Van Cao et al., 2014). Currently, sea snakes are not listed under any appendices of the Convention on International Trade in Endangered Species of Flora and Fauna (CITES), while 33% of species of sea snakes are listed as Data Deficient (DD) under the IUCN Red List (Elfes et al., 2013). These conspicuous gaps act as impediments for successful sea snake conservation strategies.

Most work on sea snakes from the Indian subcontinent are dated to colonial times (pre-1947), primarily dealing with taxonomy (Wall, 1909; Smith, 1926; Samuel, 1944), and few have looked at sea snake assemblages within the context of Indian fisheries (Kasturirangan, 1951; Lobo, 2003; Lobo, Pandav & Vasudevan, 2004; Lobo, Vasudevan & Pandav, 2005; Lobo, 2006; Padate, Baragi & Rivonker, 2009).

Twenty species of sea snakes are reported off the Indian coastline (Whitaker & Captain, 2004; Sarker et al., 2017; Ganesh et al., 2019) with higher species richness on the east coast (Lobo, 2006) as compared with the west coast (Lobo, 2003; Padate, Baragi & Rivonker, 2009). Sea snakes are protected in India under the Indian Wildlife Protection Act (1972) as a Schedule IV species (Krishnan, 1973). Collecting sea snakes or causing them harm is a criminal offence, punishable by up to 3 years in prison and a fine of up to US$350, although the implementation of this law has been logistically challenging. Sea snakes, along with cetaceans and marine turtles, use the Indian continental shelf waters as foraging and breeding grounds (Lobo, 2007) and are negatively affected by fisheries activities (Meenakumari, 2010; Elfes et al., 2013). Mechanized fishing plays a major role in India's fisheries as 82% of the fish catch comes from mechanized vessels out of which ∼50% of the catch comes from trawl boats (Central Marine Fisheries Research Institute, 2017). Since the early 1960s, trawl fisheries in India have been incentivized through institutional subsidies by the Indian government to maximize harvest rates, which has led to a rapid growth in this fishing industry (Lobo, 2007).

The objectives of this study were to: (i) describe the composition of sea snake assemblages off the Konkan coast; (ii) determine the potential threats in terms of bycatch mortalities of sea snakes across gears; and (iii) identify broader trends in fishing practices and sea snake abundances along the Konkan coast through comparisons with other studies conducted in this region across years.

2 | METHODS

2.1 | Study area

The Konkan coast is located along the central west coast of India and is about 720 km in length. Several major rivers that drain from the eastern escarpments of the Western Ghats flow into the Arabian Sea and considerably influence the geomorphology of the coast. This inflow of fresh water along with the extensive estuaries makes the Konkan coastline a highly productive ecosystem with a shallow and extended continental shelf (Widdowson & Cox, 1996; Hanamgond & Mitra, 2008). This extends along the coastal states of Maharashtra, Goa, Karnataka and northern Kerala. The coast is interspersed with a variety of marine habitats such as estuaries, mangrove forests, coral outcrops and shallow waters with depths ranging from 20 to 30 m up to 20 km offshore. This study was conducted in Malvan (16.050541 N, 73.468862 E; Figure 1), located in the state of Maharashtra, which forms the central part of the Konkan coast, between January 2016 and December 2018. Malvan has a busy fish landing centre with a large number of fish and shrimp trawlers, mechanized gill net and artisanal fisheries that operate on a daily basis (UNDP, 2013; Gupta et al., 2020).

2.1.1 | Determining the composition of sea snake assemblages off the Konkan coast

The field work was conducted over four sessions – January 2016 to May 2016, November 2016 to March 2017, November 2017 to May 2018 and October 2018 to December 2018. Sea snakes were sampled from boats using gillnets and trawl nets when they returned to port. Gillnet boats (n = 136) were sampled in the mornings

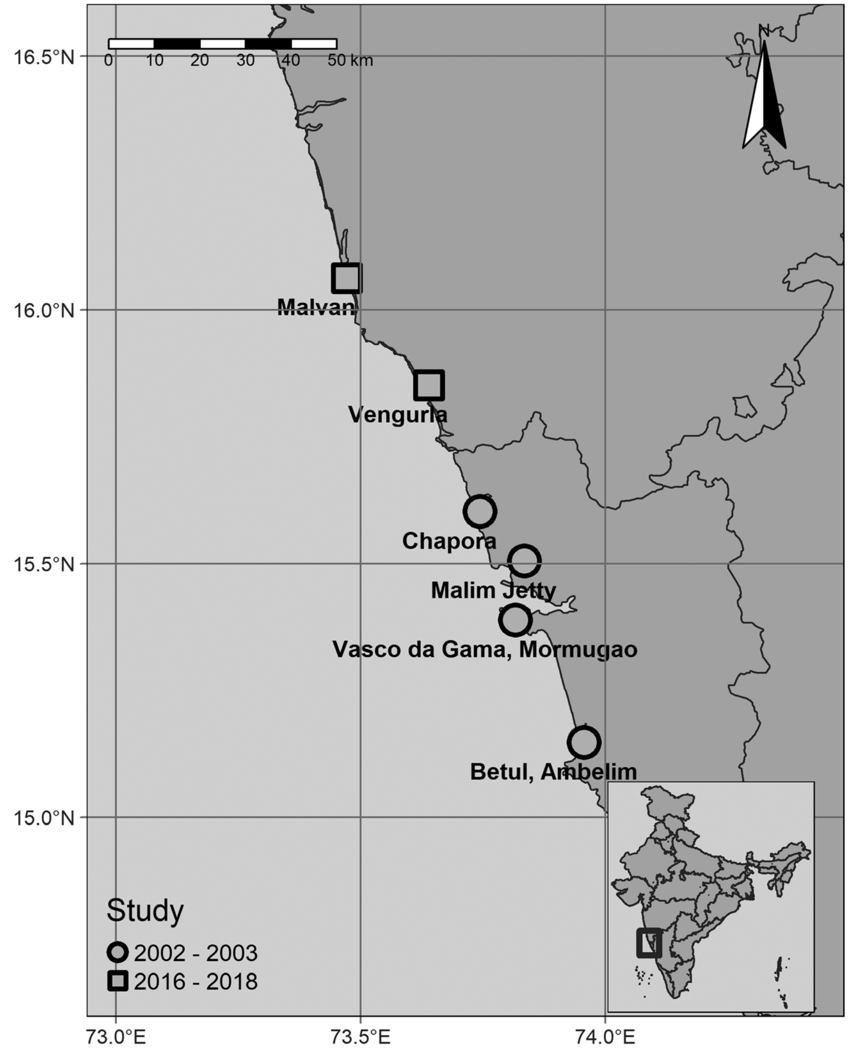


FIGURE 1 Sites surveyed during the current study (2016–2018) and by two previous studies (Padate, Baragi & Rivonker, 2009) (2006–2008) and Lobo (2002–2003) (names listed in black). Overlapping site names have been omitted for visual clarity. See Table S3 for details of study sites. Inset: Location of study sites along the west coast of India

TABLE 1 Summary of sampling effort (haul hours) in each gear during the current study

Gear type	Year	January	February	March	April	May	October	November	December
Gillnet	2016	9.00	29.00	24.00	7.00	21.00	0.00	10.00	36.50
Gillnet	2017	3.00	27.00	9.00	0.00	0.00	0.00	0.00	0.00
Gillnet	2018	206.91	112.87	128.63	25.88	51.63	43.51	62.26	109.38
Trawler	2016	0.00	8.00	9.00	9.00	8.00	0.00	0.00	0.00
Trawler	2017	84.00	105.00	52.50	0.00	0.00	0.00	0.00	15.00
Trawler	2018	49.00	50.91	30.50	11.75	0.00	0.00	11.00	5.50

between 7 and 9 a.m. and in the evening between 8 and 11 p.m. Trawlers (n = 6) were sampled in the evening from 5 to 7 p.m. Different boats were used over the course of the field sampling, and when onboard sampling was not possible all captured sea snakes (dead and alive) were brought back to shore by the boats upon an informal mutual agreement with the boat captains working in the region.

The species of sea snakes caught, abundance, fishing effort (soak time for gillnets, number of hauls and average haul duration for trawlers) were recorded for each trip. Sampling was not carried out between June and August during the seasonal closure of industrial fisheries (trawlers, gillnetters and purse seiners; Narayanakumar et al., 2017). Total sampling effort summary has been provided in Table 1.

Catch per unit effort (CPUE) for each species was calculated as abundance over total tow duration or soak time for each fishing trip. CPUE for each species was compared across months (intra-season), across years (inter-season) and across gears using linear mixed models. The effect of fishing effort (tow duration) on the encounter rate (as CPUE) of each species in each gear was also tested using linear mixed models. We used boat ID as a random effect for these analyses to control for non-independence among trips by the same boat.

2.1.2 | Determining potential threats in terms of bycatch mortalities to sea snakes across gears

Determining gear selectivity for body sizes and sex

The snout to vent length (SVL in centimetres) and sex of each individual caught in various fishing gears (trawlers, gill nets) were measured. Body sizes of snakes caught were compared across gears to check for gear selectivity on body sizes. A *Z*-test of proportion was used to determine selectivity on sex, based on the number of females caught in catches for both species.

Comparing mortality of H. curtus *and* H. schistosus *in bycatch across gillnets and trawlers*

Mortality rates for *H. curtus* and *H. schistosus* in gill nets and trawlers were calculated by:

$$\text{Mortality rates} = \frac{\text{dead snakes encountered in catch}}{\text{total snakes encountered in catch}}.$$

Mortality rates in the two species across gears were compared using a *Z*-test. The effect of tow duration/soak time on mortality rate for each species caught in gillnets and trawlers was tested using a generalized linear model.

2.1.3 | Broader trends in fishing practices and sea snake abundances along the Konkan coast through comparisons of studies across years

Determining change in assemblage composition of sea snakes along the Konkan coast

Current findings on assemblages and mortality rates were compared with Lobo, Pandav & Vasudevan (2004) and Padate, Baragi & Rivonker (2009), who conducted similar surveys of sea snakes in bycatch of trawlers in the adjacent state of Goa. Data on the abundance of *H. curtus* and *H. schistosus* and overall sampling effort, i.e. number of trips were available from these published sources. However, mortality rate in bycatch could not be inferred from Padate, Baragi & Rivonker (2009) owing to reporting of only dead specimens and not total catch. A breakdown of sampling effort for each study is provided in Table S1. Data from trawler bycatch alone from all studies were used to maintain consistency for meaningful comparisons. The differences in relative abundance of *H. curtus* and the mortality rates for both species in trawler bycatch of snakes in the various studies were statistically tested using *Z*-test of proportion.

Determining change in number of registered fishing vessels along the Konkan coast

Secondary data on the number of vessels of each type (mechanized, motorized and non-motorized) for Maharashtra and Goa were obtained from review of published literature. Variations in the number of vessels of each type from 2005 to 2019 in each state were tested using a generalized linear model. The variation in number of vessels of each craft type in Maharashtra and Goa over the same period was tested with a *t*-test for statistical significance.

All analysis was done in R version 1.2.5033 (R Core Team, 2015). Codes for analysis and data are available at https://github.com/cheesesnakes/sea-snake-bycatch

3 | RESULTS

3.1 | Composition of sea snake assemblages off the Konkan coast

3.1.1 | Composition of sea snake species in bycatch of gillnets and trawlers

A total of 394 fishing trips (329 gillnet trips and 65 trawlers trips) with total effort of 1,365.73 haul hours (916.57 gillnet haul hours and 449.16 trawler haul hours) were sampled between January 2016 and December 2018 (Table 1). *Hydrophis schistosus* ($n = 914$) was the most abundant sea snake species found in bycatch, followed by *H. curtus* ($n = 236$). Four other species were found in bycatch in both gears, namely, *Acrochordus granulatus* ($n = 1$), *H. cyanocinctus* ($n = 3$), *H. viperinus* ($n = 2$) and *H. caerulescens* ($n = 1$), but only the two dominant species have been considered for further analysis.

Catch per unit effort (CPUE) was higher in trawlers than in gillnets for both *H. schistosus* ($CPUE_{trawler} = 1.70$, $CPUE_{gill\ net} = 0.46$, $\beta = 1.22$, $\chi^2 = 73.34$, $P \ll 0.05$) and *H. curtus* ($CPUE_{trawler} = 1.2$, $CPUE_{gill\ net} = 0.42$, $\beta = 1.06$, $\chi^2 = 10.67$, $P \ll 0.05$). The CPUE was slightly higher for *H. schistosus* than *H. curtus* in gillnets ($\beta = 0.04$, $\chi^2 = 0.68$, $P = 0.4$). Conversely, more *H. curtus* were caught per unit effort in trawlers ($\beta = -0.34$, $\chi^2 = 0.24$, $P = 0.61$; Figure 2a, b). The CPUE was negatively correlated with fishing effort for both species in both gears (Table S2). The CPUE per trip varied greatly across months in both gears (Figure 2a, b) for *H. curtus* ($\chi^2_{trawler} = 23.8$, $P \ll 0.05$; $\chi^2_{gill\ net} = 23.8$, $P \ll 0.05$) and *H. schistosus* ($\chi^2_{trawler} = 8.05$, $P = 0.23$; $\chi^2_{gill\ net} = 30.32$, $P \ll 0.05$). Gillnets caught the most *H. schistosus* in the month of January and the most *H. curtus* in February, whereas, trawlers had the highest CPUE for both species in November (Figure 2a,b). The relative proportion of *H. curtus* females in trawler bycatch (0.30) was significantly lower than that in gillnets (0.59, $P \ll 0.05$). However, the proportion of *H. schistosus* females was not significantly different in trawler (0.44) and gillnet (0.51) bycatch ($P = 0.18$). Some of the females were also gravid as seen in *H. schistosus* ($n = 68$) and *H. viperinus* ($n = 1$).

3.2 | Threats in terms of bycatch mortalities to sea snakes across gears

Mortality rates were significantly higher in trawlers than in gillnets for both *H. schistosus* ($\beta = 1.81$, $\chi^2 = 8.55$, $P \ll 0.05$, MacFadden's

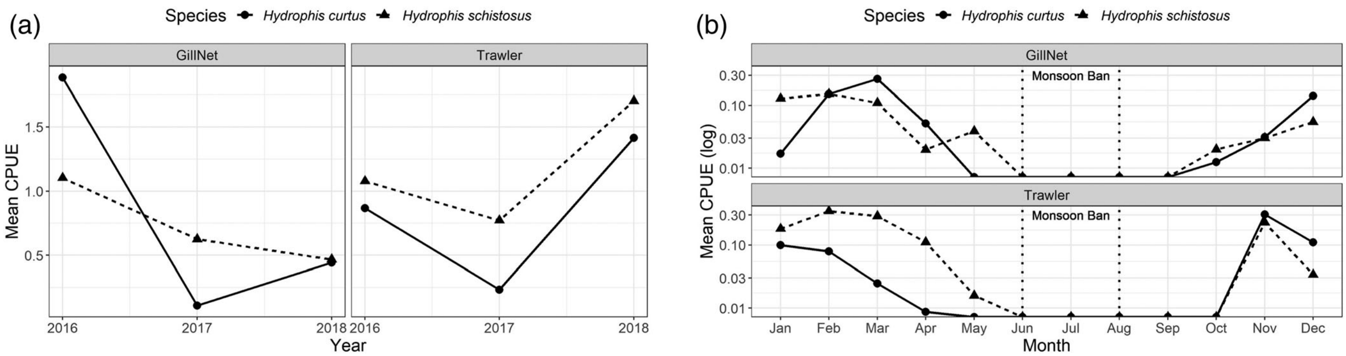
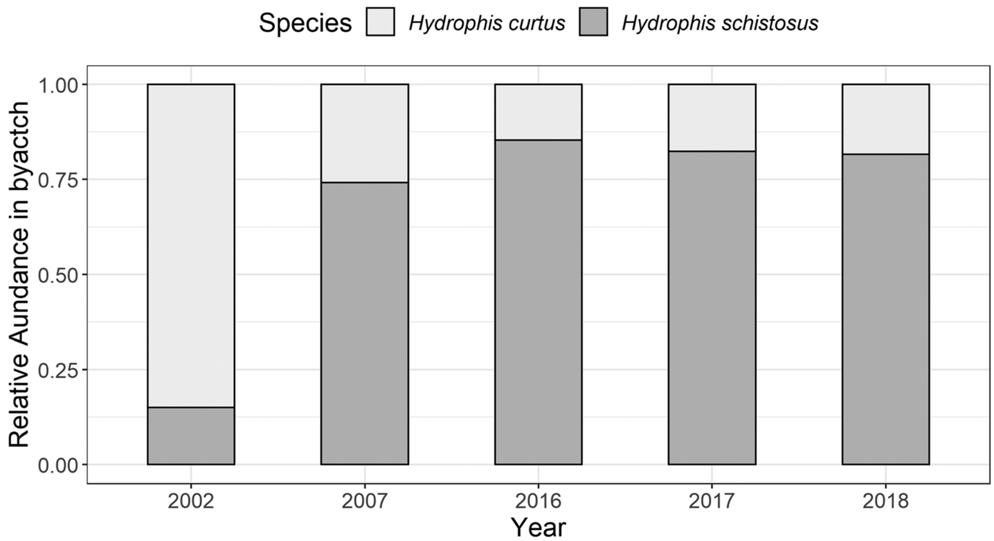


FIGURE 2 (a; left) Variation in catch per unit effort (CPUE) of *Hydrophis curtus* and *Hydrophis schistosus* in gillnets and trawlers across years in the current study. (b; right) Variation in mean CPUE (log transformed) per fishing trip of *H. curtus* and *H. schistosus* across months in the current study (data from 2018 only)

FIGURE 3 Proportion of *H. schistosus* and *H. curtus* in trawler nets recorded by Lobo (2003) and Padate, Baragi & Rivonker (2009) and in the current study (2016–2018). The proportion of *H. curtus* was found to be significantly different between Lobo (2003) and the current study ($\chi^2 = 285.26$, $P \ll 0.05$)



$R^2 = 0.11$) and *H. curtus* ($\beta = 1.80$, $\chi^2 = 5.67$, $P \ll 0.05$, MacFadden's $R^2 = 0.12$). *Hydrophis schistosus* had a significantly lower mortality rate than *H. curtus* in trawlers ($\beta = -1.51$, $\chi^2 = 5.55$, $P \ll 0.05$, MacFadden's $R^2 = 0.07$) and gillnets ($\beta = -1.53$, $\chi^2 = 5.72$, $P \ll 0.05$, MacFadden's $R^2 = 0.07$).

3.3 | Broader trends in fishing practices and sea snake abundances along the Konkan coast through comparisons of studies across years

3.3.1 | Shift in sea snake assemblages along the Konkan coast

Sampling effort varied across years in the studies that were compared (details of sampling effort by study are provided in Table S1). The relative abundance of *H. curtus* in trawler bycatch reduced significantly from 2002 to 2018 ($P \ll 0.05$; Figure 3).

3.3.2 | Trends in number of fishing vessels operating along the Konkan coast

The number of mechanized craft increased significantly from 2005 to 2019 in both Maharashtra ($\beta = 6056.42$, $P = 0.01$) and Goa ($\beta = 1102.64$, $P = 0.06$). However, the number of motorized vessels reduced slightly and non-motorized boats did not change much in both states. Maharashtra had significantly more mechanized ($P \ll 0.05$) and non-motorized ($P \ll 0.05$) crafts than Goa in all years (Figure S2).

4 | DISCUSSION

In the present study, beaked sea snake (*H. schistosus*) and spine-bellied sea snake (*H. curtus*) were the dominant species in gillnet and trawler bycatch along the Konkan coast. However, population trends in the region have changed in the past two decades, with *H. schistosus* being encountered more commonly than *H. curtus*. This could be due to a combination of many factors such as higher mortalities of *H. curtus* compared with *H. schistosus* in trawler bycatch, the increase in number of mechanized vessels in the region, differential ontogenic habitat use in both species and lower reproductive output in *H. curtus*.

Sea snakes are caught in large numbers in trawling operations throughout their distribution range (Ward, 1996; Milton, Fry & Dell, 2009). Most of the catch is accidental, as observed with the Northern Prawn Fisheries in Northern Australia since the early 1990s, where catch figures were as high as 80,000–100,000 snakes annually (Milton, 2001). *Hydrophis curtus* (previously *Lapemis hardwickii*) was reported to be a bycatch species predominantly caught by Northern Prawn Fisheries in Northern Australia in habitats which contained large rivers and valuable stocks of banana prawns (*Fenneropenaeus indicus*; Redfield, Holmes & Holmes, 1978). Ward (1996) reported that species compositions of sea snakes varied significantly at varying depths in such areas and emphasized the importance of involving commercial vessels in monitoring sea snake bycatch as their mortality was higher in trawlers that targeted prawns. Most non-target species such as sea snakes in trawl bycatch are injured or killed by the weight of the trawl catch, barotrauma (rapid changes in pressure as the animal is hauled to the surface; Wilson et al., 2014) and drowning (Wassenberg et al., 1994; Milton, 2001; Gillett et al., 2017). With limited physiological information in the present study, it is difficult to explain the higher mortality of *H. curtus* in comparison with *H. schistosus*.

However, data from our study indicate that trawling is a greater threat to sea snake survival than gill nets as both bycatch and mortality rates for both species were higher in trawl nets (Figure 2a, b). There is, however, stark seasonality in bycatch of both species across these two gears, with trawlers catching the greatest number of sea snakes early in the fishing season (around November; Figure 2a, b). This period coincides with the shift from demersal (August to October) to benthic trawling (November to May) (pers. obs.). The increased number of sea snakes in the gillnet catch (February) coincides with the reproductive period for *H. schistosus* (pers. obs.), when they probably come into shallower waters, where gillnets operate, to give birth (Lemen & Voris, 1981).

A comparison of findings with previous studies in the same region indicate a shift in abundance within species assemblages over the past two decades (Figure 3). Lobo (2003) described sea snake bycatch in trawlers in Goa and reported similar trends of higher mortality in *H. curtus* compared with *H. schistosus*; however, the encounter rate of *H. curtus* was higher than that in the present study. In concordance with the present study, Padate, Baragi & Rivonker (2009) observed that *H. curtus* represented a smaller proportion of trawler bycatch (35%) compared with *H. schistosus* (65%). Despite the greater sampling effort during the current study, encounters of sea snakes were not proportionally higher, which could possibly indicate a general decline in the sea snake population regionally.

This reduction in encounter rate with continued higher mortalities (Figure 4a, b) highlights a possible decline in population of *H. curtus* in this region. These various surveys (2003, 2009 and current) were carried out in the Konkan region at sites within 100 km of each other (Figure 1). These sites are contiguous and similar in geographic profile with large river mouths, sandy substrate outlined with rocky shores; slope and continental shelf width; fish catch and fishing practices, although the intensity of fishing may vary temporally. Sampling methodology and seasons were similar for Lobo (2003) (November 2002 to April 2003) and the present study (January–May 2016, November 2016–March 2017, and January–May 2018 and October–December 2018). However, Padate, Baragi & Rivonker (2009) only sampled sea snakes found dead in trawler nets, which may have biased their abundance estimates, although the results for species assemblages from trawlers were very similar.

Lemen & Voris (1981) compared fecundity and reproductive success in 14 species of sea snakes along the coast of Malaysia. *Hydrophis schistosus* showed more synchronized reproductive cycles than other species. Most of these were observed in the context of 'R' and 'k' selection. Minimum embryonic input meant larger clutch sizes in *H. schistosus* in comparison with *H. curtus* and *H. viperinus*,

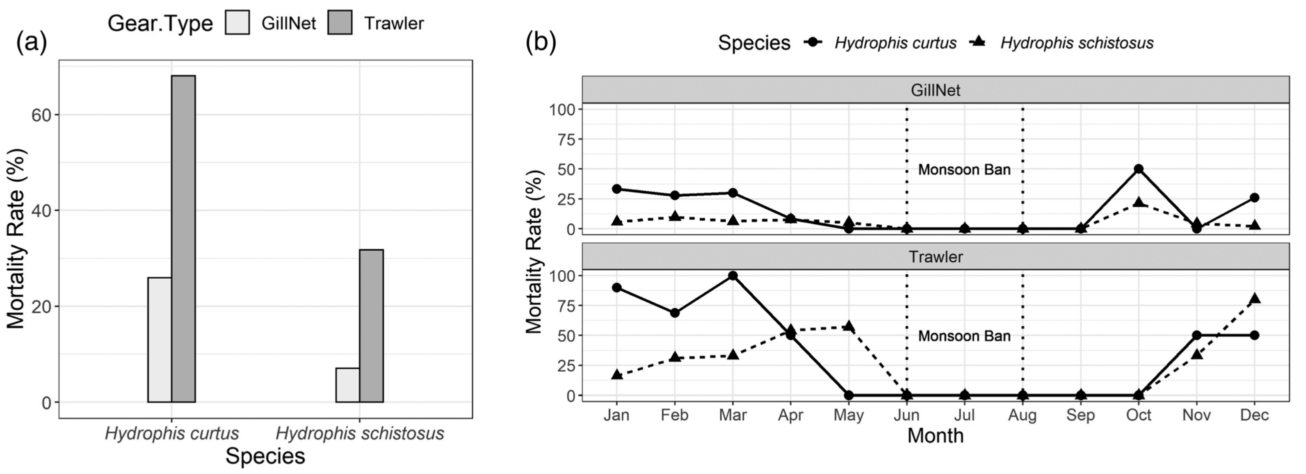


FIGURE 4 (a; left) Mortality rates of *H. curtus* and *H. schistosus* in gillnets and trawlers; (b; right) monthly trends in mortality rates during current study

which have large-sized young and a lower clutch size. We hypothesize that the advantage of greater reproductive output proved beneficial to counter population mortalities and aid population recovery of *H. schistosus* as fishing pressures continued on *H. curtus*. No gravid females of *H. curtus* were recorded but 68 dead gravid females of *H. schistosus* were encountered between the months of January and May, which overlapped with the fishing season. Thus, vulnerability of gravid females of *H. schistosus* to fishing mortality might trigger a population decline in this species if continued unchecked.

The results from our study show that adults are predominantly caught in fishing nets during the peak fishing season (December to February; Figure S1). For *H. curtus*, younger individuals were caught in November and December and large adults from January to April. *Hydrophis schistosus* is known to exhibit greater habitat plasticity than *H. curtus* and use diverse habitats, including estuaries, and may occasionally travel far upriver (Voris, 2015). However, neonates and juveniles of sea snakes often exhibit varied habitat use compared with conspecific adults (Udyawer et al., 2016a). The rivers and estuaries along the Konkan coast may possibly function as fishing refugia for juvenile snakes, particularly as mechanized fisheries are prohibited in these areas and only passive gear for fishing is allowed (Lobo, 2003; Udyawer et al., 2016b). *Hydrophis curtus* are often caught in deeper waters (>15 m; Lobo, 2003; Lobo, Pandav & Vasudevan, 2004) compared with *H. schistosus* (Wassenberg et al., 1994; Lobo, Vasudevan & Pandav, 2005), matching the findings of the present study. Lobo (2003) also recorded higher mortality of sea snakes at greater depths; however, we were unable to collect detailed information on depth at which snakes were being collected. Sea snakes diving to greater depths can remain underwater for shorter intervals of time, and therefore may be more prone to drowning in fishing nets (Heatwole & Seymour, 1975a; Heatwole & Seymour, 1975b).

Owing to their viviparous nature, dispersal in sea snakes is highly limited with strong signs of philopatry (Lukoschek & Shine, 2012) and show no specific inter-habitat movement to locate suitable nesting sites as observed in other marine reptiles such as sea kraits and sea turtles. Limited dispersal capabilities result in the formation of population clusters over time, leading to stronger genetic subdivisions (Ukuwela et al., 2016). These population clusters could qualify as 'Evolutionary Significant Units' (Karl & Bowen, 1999; Lukoschek, 2017) as they are geographically separated over large distances with unique genetic signatures. While no data exist on fishing-induced population declines in sea snakes from the Indian coastline, sea snake declines have been reported globally (Lukoschek et al., 2013; Van Cao et al., 2014). Thus, large-scale mortalities of sea snakes can lead to local population declines in areas, which could result in loss of overall genetic diversity (Dulvy et al., 2000).

Differential vulnerability to increasing fisheries and major declines in sea snake population numbers have been documented in other marine taxa such as elasmobranchs (Stevens et al., 2000). Certain life history traits of sea snakes such as low fecundity and viviparity are more similar to sharks than to their marine reptilian counterparts (sea turtles and sea kraits) that are oviparous and lay their eggs on land. Similar species assemblage shifts have been observed in community structures of skates owing to uncontrolled removal of individuals from a population (Dulvy et al., 2000). Low fecundity owing to ovo-viviparous mode of reproduction, coupled with higher mortality, have caused declines in populations of sharks, rays and skates in many other parts of their range (Stevens et al., 2000).

Despite years of research on fisheries, data on population declines and current knowledge of species assemblages of sea snakes in South Asia are lacking for informed conservation action (Elfes et al., 2013; Udyawer et al., 2018). No structured mechanism is in place to reduce the bycatch of sea snakes along the Indian coastline and implementation of bycatch reduction devices (BRD) in Indian waters has proven to be difficult for various reasons (Boopendranath, 2013). Mechanized fishing has also increased greatly over the span of a decade within Maharashtra with a 25% growth in operational vessels, while Goa has seen over 100% growth (Figure S2). A dramatic increase in fishing effort and overfishing of resources is rendering fisheries increasingly unsustainable. Fishers can no longer rely exclusively on their traditional target stocks alone to remain profitable (Lobo, 2007). Turtle excluder devices were introduced to reduce olive ridley sea turtle mortalities in the Bay of Bengal but were discontinued soon after their introduction owing to resistance from the fisher communities over loss of catch (Gopi, Pandav & Choudhury, 2007). Resistance to the use of BRD was also due to the increasing reliance on low value bycatch or 'trash fish' destined for fishmeal industries (Lobo, 2007).

India is a signatory to the Code of Conduct for Responsible Fisheries as per the Food and Agriculture Organization (Ramachandran, Vipinkumar & Shinoj, 2017). The Central Institute of Fisheries Technology has recommended bycatch reduction policies tailored for Indian fisheries (Boopendranath, 2013). However, implementation has been challenging owing to major institutional capacity deficits. Gupta et al. (2020) used a Mitigation Hierarchy Framework to address elasmobranch bycatch in Malvan under the following axes: offset (bycatch tax), remediation (post capture live release; bycatch reduction devices), minimization (gear modifications) and avoidance (spatio-temporal closures). Fishermen were keen on onboard measures to reduce mortality such as immediate release of caught individuals, uncertain about the use of BRDs but completely opposed to spatio-temporal closures and benthic gear restrictions, citing economic losses (Gupta et al., 2020). Fishermen in Malvan and other coastal areas discard caught snakes (live and dead) as a first response, and do not intentionally kill them (pers. obs). Thus, the threat to sea snakes in the Konkan coast falling within the Maharashtra state coastline can be remediated through measures that reduce bycatch and enforcement of existing guidelines as per the Maharashtra Marine Fishing Regulation Act, 1981, such as regulating the number of active mechanized vessels, fishing in specified zones, the use of gill-nets and longlines that have low sea snake bycatch and facilitating greater participation of fishing communities for effective co-management of fisheries and conservation of ecosystems of their fishing grounds (See Rajesh, 2013 for more details).

The effects of overexploitation on marine ecosystems and species assemblages are of great concern (Levin et al., 2006). Findings from our study indicate that unregulated and highly concentrated fisheries are driving changes in sea snake assemblages. Differential responses to anthropogenic stressors have led to a major shift in sea snake assemblages in less than two decades. We need to better understand these apparent differences in vulnerabilities amongst species to fishing mortality and possible sublethal effects in order to assess the levels of threat to local populations. Even though sea snakes in India are protected by law, enforcement has proven logistically difficult. A holistic understanding of the interactions of sea snakes with fisheries can help formulate suitable conservation action for these reptiles.

ACKNOWLEDGEMENTS

We would like to thank the Office of the Nodal Officer of the United Nations Development Program-Government of India-Global Environment Facility Sindhudurg Project and Additional Principal Chief Conservator of Forests, Mangrove Cell, Maharashtra State Forest Department, Mumbai; the Office of the Principal Chief Conservator of Forests and Chief Wildlife Warden, Maharashtra State Forest Department, Nagpur; Mangrove Foundation, Mumbai and the Ruffords Small Grants Foundation, London for logistics and funding support to the study; our supervisors Dr Kartik Shanker and Dr Naveen Namboothri for their support and guidance during fieldwork and in the preparation of this manuscript; Mr Prasad Warde, Mr Sunny Patil, Ms Abhilasha Sharma, Mr Yogesh Waghmare and all the volunteers for fieldwork and data collection.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest with this publication.

ETHICAL STANDARDS

The study was previewed by an Animal Ethics Committee set up by Dakshin Foundation. Relevant and necessary field permit letters were sought from the Maharashtra State Forest Department and Maharashtra State Biodiversity Board.

ORCID

Chetan Rao https://orcid.org/0000-0001-7950-4065
Shawn Dsouza https://orcid.org/0000-0002-0245-9531
Trisha Gupta https://orcid.org/0000-0002-2329-6540
Muralidharan Manoharakrishnan https://orcid.org/0000-0002-2252-2577

REFERENCES

Alverson, D.L., Freeberg, M.H., Murawski, S.A. & Pope, J.G. (1994). *A global assessment of fisheries bycatch and discards*. Rome: Food and Agriculture Organization.

Boopendranath, M.R. (2013). Biodiversity conservation technologies in fisheries. *Journal of Aquatic Biology & Fisheries*, 1(1), 14–26. http://keralamarinelife.in/2013Volume1-12.html

Central Marine Fisheries Research Institute. (2017). Annual Report 2016–17. Kochi, India: Central Marine Fisheries Research Institute.

Dulvy, N.K., Metcalfe, J.D., Glanville, J., Pawson, M.G. & Reynolds, J.D. (2000). Fishery stability, local extinctions, and shifts in community structure in skates. *Conservation Biology*, 14(1), 283–293. https://doi.org/10.1046/j.1523-1739.2000.98540.x

Elfes, C.T., Livingstone, S.R., Lane, A., Lukoschek, V., Sanders, K., Courtney, A.J. et al. (2013). Fascinating and forgotten: The conservation status of the world's sea snakes. *Herpetological Conservation and Biology*, 8(1), 37–52. http://www.herpconbio.org/contents_vol8_issue1.html

Ganesh, S., Nandhini, T., Samuel, V., Sreeraj, C., Abhilash, K., Purvaja, R. et al. (2019). Marine snakes of Indian coasts: Historical resume, systematic checklist, toxinology, status, and identification key. *Journal of Threatened Taxa*, 11(1), 13132–13150. https://doi.org/10.11609/jott.3981.11.1.13132-13150

Gillett, A.K., Ploeg, R., Flint, M. & Mills, P.C. (2017). Postmortem examination of Australian sea snakes (Hydrophiinae): Anatomy and common pathologic conditions. *Journal of Veterinary Diagnostic Investigation*, 29(5), 593–611. https://doi.org/10.1177/1040638717710056

Gopi, G.V., Pandav, B. & Choudhury, B.C. (2007). Efficacy of turtle excluder devices on incidental captures of olive ridley sea turtles (*Lepidochelys olivacea*) in the trawl fisheries of Orissa, India. *B.C.G: Testudo*, 6(4), 67–73. https://www.researchgate.net/profile/Gopi-G-V-2/publication/261207374_Efficacy_of_Turtle_Excluder_Device_on_incidental_captures_of_sea_turtles_and_trawl_fisheries_of_Orissa_with_implications_for_conservation/links/00463534ccf0f2c240000000/Efficacy-of-Turtle-Excluder-Device-on-incidental-captures-of-sea-turtles-and-trawl-fisheries-of-Orissa-with-implications-for-conservation.pdf

Gray, J.S. (1997). Marine biodiversity: Patterns, threats and conservation needs. *Biodiversity and Conservation*, 175(1), 153–175. https://doi.org/10.1023/A:1018335901847

Gupta, T., Booth, H., Arlidge, W., Rao, C., Muralidharan, M., Namboothri, N. et al. (2020). Mitigation of elasmobranch bycatch in trawlers: A case study in Indian fisheries. *Frontiers in Marine Science*, 7(571), 1–17. https://doi.org/10.3389/fmars.2020.00571

Hall, M.A., Alverson, D.L. & Metuzals, K.I. (2000). By-catch: Problems and solutions. *Marine Pollution Bulletin*, 41(1–6), 204–219. https://doi.org/10.1016/S0025-326X(00)00111-9

Hanamgond, P.T. & Mitra, D. (2008). Evolution of Malvan Coast, Konkan, West Coast of India – A case study using remote sensing data. *Journal of Coastal Research*, 24(3), 672–678. https://doi.org/10.2112/06-0692.1

Heatwole, H. (1997). Marine snakes: Are they a sustainable resource? *Wildlife Society Bulletin*, 25(4), 766–772. https://www.jstor.org/stable/3783721

Heatwole, H. & Seymour, R. (1975a). Diving physiology. In: W.A. Dunson (Ed.) *The biology of sea snakes*. Baltimore, MD: University Park Press, pp. 289–327.

Heatwole, H. & Seymour, R. (1975b). Pulmonary and cutaneous oxygen uptake in sea snakes and a file snake. *Comparative Biochemistry and Physiology Part A: Physiology*, 51(2), 399–405. https://doi.org/10.1016/0300-9629(75)90387-4

Ineich, I., Bonnet, X., Brischoux, F., Kulbicki, M., Séret, B. & Shine, R. (2007). Anguilliform fishes and sea kraits: Neglected predators in coral-reef ecosystems. *Marine Biology*, 151(2), 793–802. https://doi.org/10.1007/s00227-006-0527-6

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J. et al. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science*, 293(5530), 629–638. https://doi.org/10.1126/science.1059199

Karl, S.A. & Bowen, B.W. (1999). Evolutionary significant units versus geopolitical taxonomy: Molecular systematics of an endangered sea turtle (genus *Chelonia*). *Conservation Biology*, 13(5), 990–999. https://doi.org/10.1046/j.1523-1739.1999.97352.x

Kasturirangan, L.R. (1951). Placentation in the sea-snake, *Enhydrina schistosa* (Daudin). *Proceedings of the Indian Academy of Sciences – Section B*, 34(1), 1–32. https://doi.org/10.1007/BF03050555

Krishnan, M. (1973). The Wildlife (Protection) Act of 1972: A critical appraisal. *Economic and Political Weekly*, 8(11), 564–566. https://www.jstor.org/stable/4362432

Lemen, C.A. & Voris, H.K. (1981). A comparison of reproductive strategies among marine snakes. *The Journal of Animal Ecology*, 50(1), 89–101. https://doi.org/10.2307/4033

Levin, P.S., Holmes, E.E., Piner, K.R. & Harvey, C.J. (2006). Shifts in a Pacific Ocean fish assemblage: The potential influence of exploitation. *Conservation Biology*, 20(4), 1181–1190. https://doi.org/10.1111/j.1523-1739.2006.00400.x

Lewison, R.L., Crowder, L.B., Wallace, B.P., Moore, J.E., Cox, T. & Zydelis, R. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proceedings of the National Academy of Sciences of the United States of America*, 111(4), 5271–5276. https://doi.org/10.1073/pnas.1318960111

Lobo, A.S. (2003). *Estimating sea Snake diversity using trawler bycatch along the coast of Goa*. MSc Thesis, Saurashtra University, Gujarat, India.

Lobo, A.S. (2006). *Sea snakes of the Gulf of Mannar Marine National Park. The Species and their Conservation*. Report submitted to Rufford Foundation.

Lobo, A.S. (2007). The bycatch problem. *Resonance*, 12(5), 60–70. https://doi.org/10.1007/s12045-007-0051-0

Lobo, A.S., Pandav, B. & Vasudevan, K. (2004). Weight-length relationship in two species of marine snakes along the coast of Goa, Western Ghats. *Hamadryad*, 29(1), 89–93. https://www.researchgate.net/profile/Karthikeyan-Vasudevan-3/publication/242659852_WEIGHT-LENGTH_RELATIONSHIPS_IN_TWO_SPECIES_OF_MARINE_SNAKES_ALONG_THE_COAST_OF_GOA_WESTERN_INDIA/links/53d65ef20cf2a7fbb2ea9f0f/WEIGHT-LENGTH-RELATIONSHIPS-IN-TWO-SPECIES-OF-MARINE-SNAKES-ALONG-THE-COAST-OF-GOA-WESTERN-INDIA.pdf

Lobo, A.S., Vasudevan, K. & Pandav, B. (2005). Trophic ecology of *Lapemis curtus* (Hydrophiinae) along the Western Coast of India. *Copeia*, 2005(3), 637–641. https://doi.org/10.1643/CH-04-076R1

Lukoschek, V. (2017). Congruent phylogeographic patterns in a young radiation of live-bearing marine snakes: Pleistocene vicariance and the conservation implications of cryptic genetic diversity. *Diversity and Distributions*, 24(3), 325–340. https://doi.org/10.1111/ddi.12687

Lukoschek, V., Beger, M., Ceccarelli, D., Richards, Z. & Pratchett, M. (2013). Enigmatic declines of Australia's sea snakes from a biodiversity hotspot. *Biological Conservation*, 166, 191–202. https://doi.org/10.1016/j.biocon.2013.07.004

Lukoschek, V. & Shine, R. (2012). Sea snakes rarely venture far from home. *Ecology and Evolution*, 2(6), 1113–1121. https://doi.org/10.1002/ece3.256

McConnaughey, R.A., Hiddink, J.G., Jennings, S., Pitcher, C.R., Kaiser, M.J., Suuronen, P. et al. (2019). Choosing best practices for managing impacts of trawl fishing on seabed habitats and biota. *Fish and Fisheries*, 21(2), 319–337. https://doi.org/10.1111/faf.12431

Meenakumari, B. (2010). Responsible fishing in coastal fisheries of India. In: B. Meenakumari, M.R. Boopendranath, L. Edwin, T.V. Sankar, N. Gopal, G. Ninan (Eds.) *Coastal fishery resources of India: Conservation and sustainable utilisation*. Cochin, India: Society of Fisheries Technologists (India), pp. 235–245.

Milton, D.A. (2001). Assessing the susceptibility to fishing of populations of rare trawl bycatch: Sea snakes caught by Australia's Northern Prawn Fishery. *Biological Conservation*, 101(3), 281–290. https://doi.org/10.1016/S0006-3207(00)00232-9

Milton, D.A., Fry, G.C. & Dell, Q. (2009). Reducing impacts of trawling on protected sea snakes: By-catch reduction devices improve escapement and survival. *Marine and Freshwater Research*, 60(8), 824–832. https://doi.org/10.1071/MF08221

Narayanakumar, R., Jayasankar, J., Salim, S.S., Ganga, U. & Vivekanandan, E. (2017). Economic valuation of net social benefit of seasonal fishing ban in selected maritime states of India. *Indian Journal of Fisheries*, 64(3), 85–92. https://doi.org/10.21077/ijf.2017.64.3.65197-12

Padate, V.P., Baragi, L.V. & Rivonker, C.U. (2009). Biological aspects of sea snakes caught incidentally by commercial trawlers off Goa, west coast of India. *Journal of Threatened Taxa*, 12(1), 609–616. https://doi.org/10.11609/JoTT.o2253.609-16

Pears, R.J., Morison, A.K., Jebreen, E.J., Dunning, M.C., Pitcher, C.R., Courtney, A.J. et al. (2012). *Ecological risk assessment of the East Coast otter trawl fishery in the great barrier reef Marine Park: Technical report*. Great Barrier Reef Marine Park Authority.

R Core Team. (2015). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing.

Rajesh, K.M. (2013). *Fisheries legislation in India*. Central Marine Fisheries Research Institute, Kochi. Available at: http://eprints.cmfri.org.in/id/eprint/9871

Ramachandran, C., Vipinkumar, V.P. & Shinoj, P. (2017). Responsible fisheries – A prelude to the concept, context and praxis. In: *Structure and function of the marine ecosystem: Fisheries*. Kochi, India: ICAR-CMFRI, pp. 388–403.

Redfield, J.A., Holmes, J.C. & Holmes, R.D. (1978). Sea snakes of the eastern Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research*, 29(3), 325–334. https://doi.org/10.1071/MF9780325

Samuel, M. (1944). Studies on the corpus luteum in *Enhydrina schistosa* (Daudin) and *Hydrophis cyanocinctus* (Daudin) of the Madras coast. *Proceedings of the Indian Academy of Sciences- Section B*, 20, 143–174. https://www.ias.ac.in/article/fulltext/secb/020/05/0143-0174

Sanders, K.L., Lee, M.S.Y., Bertozzi, T. & Rasmussen, A.R. (2013). Multilocus phylogeny and recent rapid radiation of the viviparous sea snakes (Elapidae: Hydrophiinae). *Molecular Phylogenetics and Evolution*, 66(3), 575–591. https://doi.org/10.1016/j.ympev.2012.09.021

Sarker, A.R., Sanders, K.L., Ukuwela, K. & Jamam, M.F. (2017). Sea snakes of Bangladesh: A preliminary survey of Cox's Bazar District with notes on diet, reproduction, and conservation status. *Herpetological Conservation and Biology*, 12(2), 384–393. http://www.herpconbio.org/Volume_12/Issue_2/RazzaqueSarker_etal_2017.pdf

Smith, M.A. (1926). *Monograph of the sea-snakes (Hydrophiidae)*. London: Trustees of the British Museum (Natural History).

Stevens, J.D., Bonfil, R., Dulvy, N.K. & Walker, P.A. (2000). The effects of fishing on sharks, rays, and chimaeras (Chondrichthyans), and the implications for marine ecosystems. *ICES Journal of Marine Science*, 57(3), 476–494. https://doi.org/10.1006/jmsc.2000.0724

Tu, A.T. (1974). Sea snake investigation in the Gulf of Thailand. *Journal of Herpetology*, 8(3), 201–210. https://doi.org/10.2307/1563165

Udyawer, V., Barnes, P., Bonnet, X., Brischoux, F., Crowe-Riddell, J., D'Anastasi, B. et al. (2018). Future directions in the research and management of marine snakes. *Frontiers in Marine Science*, 5, 1–16. https://doi.org/10.3389/fmars.2018.00399

Udyawer, V., Read, M.A., Hamann, M., Heupel, M.R. & Simpfendorfer, C.A. (2016a). Importance of shallow tidal habitats as refugia from trawl fishing for sea snakes. *Journal of Herpetology*, 50(4), 527–533. https://doi.org/10.1670/15-026

Udyawer, V., Simpfendorfer, C.A., Read, M.A., Hamann, M. & Heupel, M.R. (2016b). Exploring habitat selection in sea snakes using passive acoustic monitoring and Bayesian hierarchical models. *Marine Ecology Progress Series*, 546, 249–262. https://doi.org/10.3354/meps11632

Ukuwela, K.D., Lee, M.S., Rasmussen, A.R., De Silva, A., Fry, B.G., Ghezellou, P. et al. (2016). Evaluating the drivers of Indo-Pacific biodiversity: Speciation and dispersal of sea snakes (Elapidae: Hydrophiinae). *Journal of Biogeography*, 43(2), 243–255. https://doi.org/10.1111/jbi.12636

United Nations Development Programme. (2013). *Mainstreaming coastal and marine biodiversity conservation into production sectors in the Sindhudurg coast*. Maharashtra: Progress Report, UNDP.

Van Cao, N., Tao, N.T., Moore, A., Montoya, A., Rasmussen, A.R., Broad, K. et al. (2014). Sea snake harvest in the Gulf of Thailand. *Conservation Biology*, 28(6), 1677–1687. https://doi.org/10.1111/cobi.12387

Voris, H.K. (1972). The role of sea snakes (Hydrophiidae) in the trophic structure of coastal ocean communities. *Journal of the Marine Biological Association of India*, 14(2), 429–442.

Voris, H.K. (2015). Marine snake diversity in the mouth of the Muar River, Malaysia. *Tropical Natural History*, 15(1), 1–21. https://li01.tci-thaijo.org/index.php/tnh/article/view/103083

Voris, H.K. & Voris, H.H. (1983). Feeding strategies in marine snakes: An analysis of evolutionary, morphological, behavioral and ecological relationships. *American Zoologist*, 23(2), 411–425. https://doi.org/10.1093/icb/23.2.411

Wall, F. (1909). *A monograph of the sea snakes (Hydrophiinae)*. Calcutta: Asiatic Society.

Ward, T.M. (1996). Sea snake by-catch of prawn trawlers on the northern Australian continental shelf. *Marine and Freshwater Research*, 47(4), 631–635. https://doi.org/10.1071/MF9960631

Wassenberg, T.J., Milton, D.A. & Burridge, C.Y. (2001). Survival rates of sea snakes caught by demersal trawlers in northern and eastern Australia. *Biological Conservation*, 100(3), 271–280. https://doi.org/10.1016/S0006-3207(01)00031-3

Wassenberg, T.J., Salini, J.P., Heatwole, H. & Kerr, J.D. (1994). Incidental capture of sea-snakes (Hydrophiidae) by prawn trawlers in the Gulf of Carpentaria, Australia. *Australian Journal of Marine and Freshwater Research*, 45(3), 429–443. https://doi.org/10.1071/MF9940429

Whitaker, R. & Captain, A. (2004). *Snakes of India – The field guide*. Chennai: Draco Books.

Widdowson, M. & Cox, K.G. (1996). Uplift and erosional history of the Deccan Traps, India: Evidence from laterites and drainage patterns of the Western Ghats and Konkan Coast. *Earth and Planetary Science Letters*, 137(1), 57–69. https://doi.org/10.1016/0012-821X(95)00211-T

Wilson, S.M., Raby, G.D., Burnetta, N.J., Hinch, S.G. & Cooke, S.J. (2014). Looking beyond the mortality of bycatch: Sublethal effects of incidental capture on marine animals. *Biological Conservation*, 171, 61–72. https://doi.org/10.1016/j.biocon.2014.01.020

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Rao, C., Dsouza, S., Gupta, T., Manoharakrishnan, M. & Lobo, A.S. (2021). Fisheries induced shift in sea snake community assemblages along the Konkan coast, India. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 1–10. https://doi.org/10.1002/aqc.3658