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RESEARCH ARTICLE

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Incidental capture and mortality of sea turtles in the industrial double-rig-bottom trawl fishery in south-eastern Brazil

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Abstract

1. Incidental capture by fisheries is one of the principal threats to sea turtles. This study analysed spatial and temporal patterns of sea turtle bycatch, and estimated the direct initial mortality rate of these animals, in the industrial double-rig-bottom trawl fishery in south-eastern Brazil. This is also the first attempt to relate bycatch/at-sea mortality in bottom trawling to stranded turtles found along the adjacent coast.
2. The fishery was monitored from October 2015 to April 2018 through data collected voluntarily by the captains of eight industrial double-rig trawlers. Two hundred and one sea turtles were captured during 9362 tows (43,657.52 trawling hours), resulting in a catch per unit effort (CPUE) of 0.0025 ± 0.0032 turtles h^{-1} with a standard net of 30.5 m headrope, with no significant difference between the estimated CPUEs for licensed shrimp and demersal fish trawlers.
3. *Caretta caretta* (52.24%) and *Lepidochelys olivacea* (38.81%) were the most frequently captured species. According to Generalized Linear Models, *C. caretta* bycatch was significantly higher during winter, at lower latitudes (−24° to −23°) and higher longitudes (−42° to −40°), while the *L. olivacea* bycatch was significantly higher at higher latitudes (−23° to −21°). The direct initial mortality rate of sea turtles in the shrimp trawlers was 7.65 ± 3.85%. However, none of the dead individuals subsequently released with plastic tags (n = 10) were found stranded on the coast. Mortality was not significantly related to the depth or duration of the trawling.
4. The results of this study suggest the need for improvements to the current management of the bottom trawl fishery in Brazil, moving from a species-based to a spatial and seasonal-based approach. There is also a need to develop turtle excluder devices adapted to local fishing conditions.

KEYWORDS

beach, coastal, conservation, endangered species, fishing, legislation, reptiles, trawling

1 | INTRODUCTION

Five sea turtle species occur in Brazil: green turtle (*Chelonia mydas*, Linnaeus, 1758), loggerhead turtle (*Caretta caretta*, Linnaeus, 1758), hawksbill turtle (*Eretmochelys imbricata*, Linnaeus, 1766), olive ridley turtle (*Lepidochelys olivacea*, Eschscholtz, 1829) and leatherback turtle (*Dermochelys coriacea*, Vandelli, 1761). They are present in several different ecosystems throughout their lives, where they face various anthropogenic threats (Marcovaldi & Marcovaldi, 1999). Bycatch in fishing gear is often considered one of the major causes of mortality for sea turtles (Casale et al., 2010; Tomás, Gozalbes, Raga, & Godley, 2008).

In Brazil, all sea turtle species are included in the Red Book of the Brazilian Fauna Threatened by Extinction (Chico Mendes Institute for Biodiversity Conservation/Ministry of Environment – ICMBio/MMA 2018) and are protected by Brazilian law (Law No. 5197 of 1967, SUDEPE Ordinance No. 005 of 1986, Law No. 9605 of 1998, MMA Ordinance No. 444 of 2014). There is also specific legislation to reduce incidental capture by certain fishing gear types, such as the mandatory use of turtle excluder devices (TEDs) on shrimp trawlers larger than 11 m in length (MMA Normative Instruction No. 31 of 2004) and the mandatory use of circle hooks, uncouplers and hook cutters in the horizontal surface longline fishery (MDIC Interministerial Ordinance No. 74 of 2017).

However, many turtles are still incidentally captured by several fisheries, with bottom trawling, gillnets and longlines considered the most impactful (Domingo et al., 2006; Oravetz, 1999). Bottom trawling is a common fishery method used by artisanal and industrial fleets along the south-eastern and southern regions of Brazil (Perez, Pezzuto, Rodrigues, Valentini, & Vooren, 2001). The bottom trawler fleet registered in the state of Rio de Janeiro in 2015 comprised 662 vessels (15% of the south-eastern–southern Brazil trawler fleet). The registered fleet comprised 73% artisanal vessels authorized to target sea-bob shrimp (*Xiphopenaeus kroyeri*), 14.6% artisanal vessels for pink shrimp (*Farfantepenaeus paulensis*, *F. brasiliensis* and *F. subtilis*), 10.4% pink-shrimp industrial vessels and 2% industrial vessels for demersal fishes (data from the Brazilian Ministry of Fishery and Aquaculture apud Martins, 2017).

Regardless of the target species, trawling has low selectivity, generating a large volume of bycatch and greatly impacting some sea turtle populations in the world, mainly *C. caretta* (Casale, Laurent, & De Metrio, 2004; Lucchetti & Sala, 2010; Oravetz, 1999). In Brazil, few studies have directly evaluated the bycatch in trawlers, with *C. caretta* being the most affected sea turtle in the south (Guterres et al., 2014; Monteiro, Estima, & Secchi, 2013), as well as in the south-east, where *L. olivacea* also has a high bycatch rate (Guimarães, Tavares, & Monteiro-Neto, 2018). Incidental capture in bottom trawls has already been suggested as the main cause of *L. olivacea* strandings in the north-east (Castilhos, 2016; Silva, Castilhos, Santos, Brondízio, & Bugoni, 2010) and *C. caretta* in the south (Monteiro et al., 2016).

Strandings of the five species of sea turtles have regularly been recorded on the south-eastern coast of Brazil (Reis, Pereira, et al., 2010; Reis, Goldberg, & Lopez, 2017; Reis, Silveira, & Siciliano, 2009; Werneck et al., 2018). However, the cause-and-effect relationship between the bycatch/mortality in bottom trawling and these strandings has never been verified. Improved information and knowledge about the direct impact of the trawl fleets on sea turtle populations would inform improved management of the fisheries through reduced bycatch and mortality of sea turtles.

The objectives of the present study were: (i) to analyse the distribution and seasonal variations of fishing operations and incidental captures of sea turtles of the monitored industrial double-rig-bottom trawlers; (ii) to identify the species, life stages and sex of sea turtles incidentally captured by this fishery; (iii) to estimate the catch of sea turtles per unit of effort (CPUE), as well as the direct initial mortality rate; (iv) to verify those abiotic variables (hour, tow duration, water depth, latitude, longitude and season) that influence the bycatch and the direct initial mortality of these animals; and (v) to relate bycatch/at-sea mortality in bottom trawling with stranded turtles found along the coast of the state of Rio de Janeiro.

2 | METHODS

2.1 | STUDY AREA

The monitored trawlers operate along the Southwestern Atlantic, from 25°39′40′′ S 47°07′10′′ W (southern limit) to 21°40′60′′ S 40°31′15′′ W (northern limit) and land their catch in the port city of Niterói – Rio de Janeiro state (22°52′21′′ S 43°07′24′′ W; Figure 1). The continental shelf of this region consists of soft bottoms and reaches a maximum width of 250 km between the latitudes of 23° and 28° S and a minimum of 60 km at 21° S (Rossi-Wongtschowski et al., 2006).

The most striking oceanographic feature in this region is the occurrence of coastal upwelling. The South Atlantic Central Water, which is the deep, cold, nutrient-rich water mass of the outer shelf, penetrates the continental shelf towards the coast, especially between late spring and summer, fertilizes the euphotic zone, increases primary production and, consequently, supports the development of all trophic levels, increasing fishery resources (Rossi-Wongtschowski et al., 2006).

2.2 | DATA COLLECTION

Between October 2015 and April 2018, the fishing trips of eight industrial double-rig-bottom trawlers were recorded through a voluntary logbook programme completed by the vessel captains, who were trained to collect the data. Seven trawlers were licensed to catch shrimp and some non-target species (vessel length, mean ± SD = 20.9 ± 2.0 m, range = 18.0–23.0 m; engine power, mean ± SD = 327.3 ± 49.3 hp, range = 240–375 hp) and one was licensed to catch demersal fishes (vessel length, 18.6 m; engine power, 290 hp). The net upper rope length (headrope) was consistent between all trawlers, measuring 28.0 m. All nets were 28–30 m in length with mesh size between 27 and 30 mm. Trawling speed was variable from 1.8 to 2.7 nm h^{-1}, while a constant speed is assumed for equivalence (in terms of area fished) of tows of the same duration.

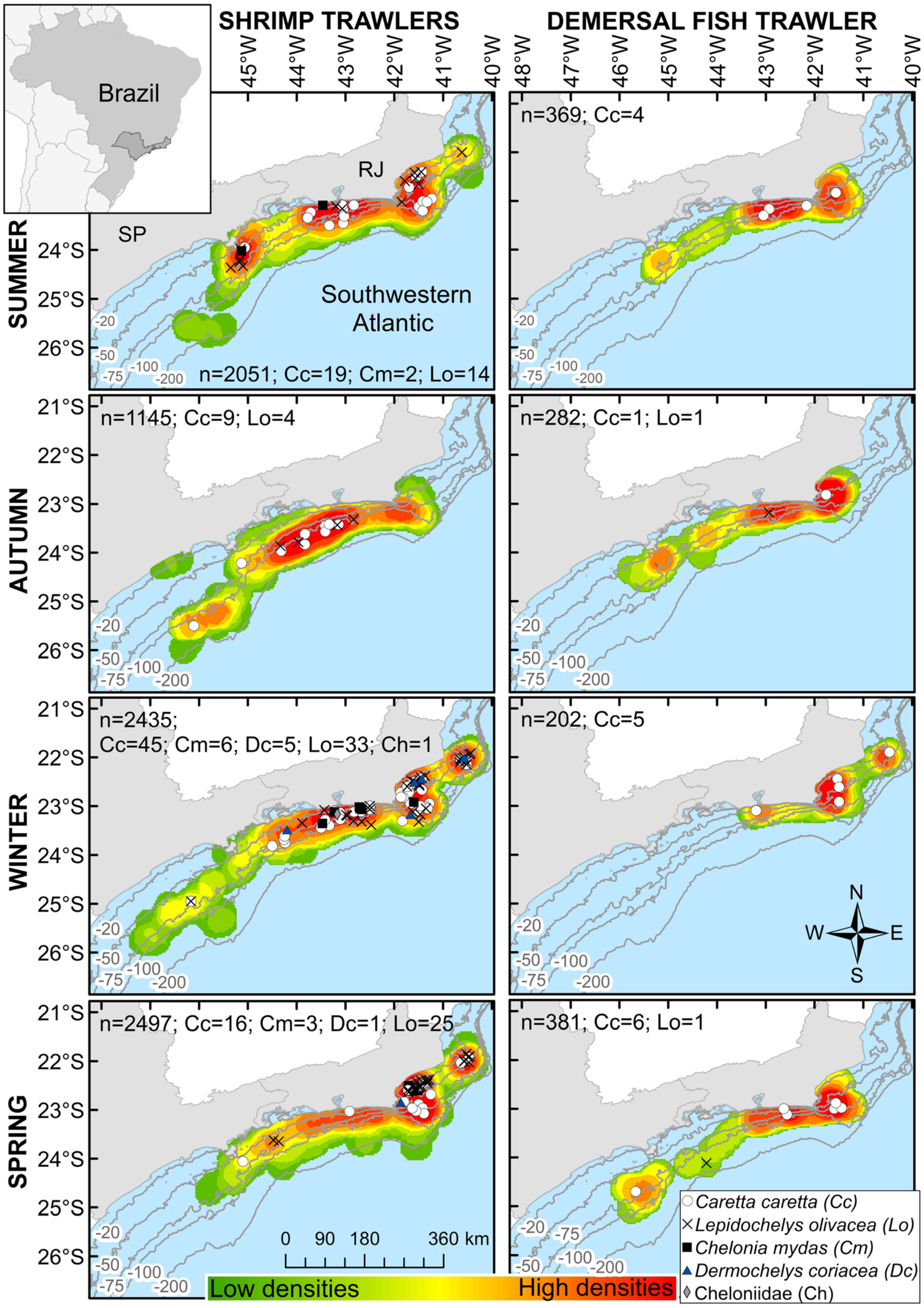

FIGURE 1 Spatial distribution of shrimp and demersal fish double-rig-bottom trawling represented by point density maps and bycatch of sea turtles per season (2015–2018). '*n*' represents the number of recorded tows. 'Cc', 'Cm', 'Dc', 'Lo' and 'Ch' (unknown Chelonid species) represent the number of sea turtle bycatch per species/family. The lines in the Southwestern Atlantic indicate the isobaths of 20, 50, 75, 100 and 200 metres. SP, São Paulo; RJ, Rio de Janeiro.

The operation period of the trawlers varied individually, according to the availability of the captains, stoppages for vessel maintenance and the closure of the shrimp fishing season in south-eastern Brazil, which occurs between 1 March and 31 May (IBAMA Normative Instruction No. 189 of 2008).

The date, hour, latitude, longitude and depth (for deployment and collection of trawls) were recorded for all tows, following Guimarães et al. (2018). The species, the curved carapace length (CCL) (Bolten, 1999), sex (only for adult individuals, according to Wibbels, 1999) and condition (alive/injured or dead, following Gerosa & Aureggi, 2001) were recorded for incidentally captured sea turtles. The classification of the turtle life stages (juveniles and subadults/adults) was based on carapace length, drawn from published datasets (Table 1). Dead turtles had numbered plastic tags affixed to their shoulders (Figure 2b) and were returned to the sea, to verify if they would be found stranded on the coast of the state of Rio de Janeiro, thus providing a link between bycatch in this fishery and stranded turtles recorded on the coast. This analysis focused on the coast of Rio de

TABLE 1 Classification of life stages of sea turtles, based on the minimum curved carapace length (CCL, cm) of females nesting on Brazilian beaches (adults) per species and according to the literature.

Species	Juveniles	Subadults/Adults
Caretta caretta	<83	≥83 (Baptistotte, Thomé, & Bjorndal, 2003)
Chelonia mydas	<90	≥90 (Almeida, Moreira, et al., 2011)
Dermochelys coriacea	<139	≥139 (Thomé et al., 2007)
Lepidochelys olivacea	<62	≥62 (Silva, Castilhos, Lopez, & Barata, 2007)

Janeiro because it was where the fishing effort of the monitored vessels was concentrated. The vessels' captains took photos/videos for confirmation of the species identification by the researchers. This research was conducted under the System of Authorization and Information on Biodiversity – SISBIO licence number 54067-1.

Three beach monitoring programmes (BMPs) monitored the entire coast of Rio de Janeiro state (approximately 1317 km) and recorded stranded sea turtles throughout the study period. The BMPs were authorized by the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA/MMA), as required by federal environmental licensing of PETROBRAS activities for the production and disposal of oil and natural gas in the Santos and Campos Basin (PETROBRAS, 2017; Werneck et al., 2018), except in the municipalities of Campos dos Goytacazes and São João da Barra (22°05′34.8′′ S 41°08′03.8′′ W to 21°37′09.1′′ S 41°00′53.3′′ W; 66 km of extension), where the BMP was associated with the state licensing of Açu Port. All BMPs featured daily patrols for stranded sea turtles, and also involved a collaborative stranding network, in which beach cleaners, public agencies and the local citizens contacted the BMPs to collect stranded turtles (see Werneck et al. (2018) for more information).

2.3 | DATA ANALYSIS

The results of fishery monitoring were collated in two ways: (i) as a whole, considering the double-rig-bottom trawling is a single fishing modality; and (ii) by target species (shrimp/bycatch of marketable species or demersal fishes) of the trawlers, which is how fisheries are managed in Brazil (according to MPA/MMA Normative Instruction No. 10 of 2011).

To analyse the spatio-temporal distribution of the tows, point density maps were generated per season (summer, December to February; autumn, March to May; winter, June to August; spring, September to November). All recorded tows and bycatch of sea turtles per species were plotted on the maps using latitude and longitude recorded at the time of the trawl deployment. Maps were generated using ArcMap 10.5.

Differences between the total duration of the recorded tows (hours) per season/year were tested by the Kruskal–Wallis test. The catch per unit effort (CPUE) was calculated in two ways: (i) from the number of incidentally captured sea turtles divided by the number of recorded tows; and (ii) from the standardized effort for a single trawl with 30.5 m headrope length, as proposed by Henwood and Stuntz (1987). The standardized effort (E) was estimated according to Alió, Marcano, and Altuve (2010):

$$E = nt\left(\frac{H}{30.5}\right)$$

where n is the number of nets (= 2), t is the duration of the tows (h) and H is the headrope length (= 28 m).

The standardized CPUE and 95% confidence intervals (95% CI) were estimated according to Snedecor and Cochran (1967):

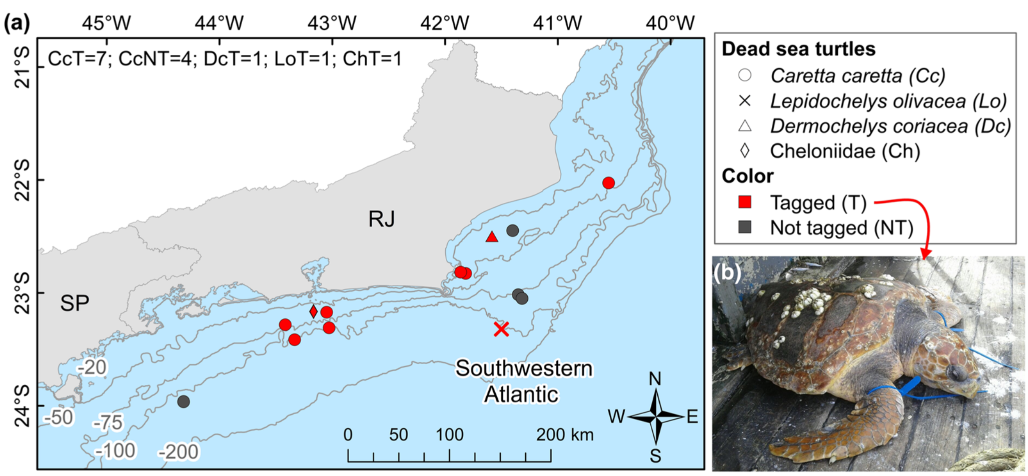

FIGURE 2 (a) Spatial distribution of sea turtles retrieved dead by the double-rig-bottom shrimp trawlers; those turtles that were tagged with numbered plastic tags are marked in red. 'CcT', 'CcNT', 'DcT', 'LoT' and 'ChT' represent the number of dead sea turtles per species/family, with red fill indicating those tagged and grey indicating the untagged ones. The lines in the south-western Atlantic indicate the isobaths of 20, 50, 75, 100 and 200 m. SP, São Paulo; RJ, Rio de Janeiro. (b) Juvenile specimen of *Caretta caretta* retrieved dead by a double-rig-bottom shrimp trawler on the Rio de Janeiro coast and tagged with numbered plastic tags.

$$\mathrm{CPUE} = \frac{\sum_{i=1}^{n} Ti}{\sum_{i=1}^{n} Ei}.$$

$$\mathrm{CI} = \mathrm{CPUE} \pm 1.96\ \mathrm{sCPUE}$$

$$\mathrm{sCPUE} = \left(\frac{1}{X}\right)\sqrt{\frac{\sum_{i=1}^{n} (Ti - \mathrm{CPUE}\ Ei)^2}{n(n-1)}}$$

where Ti is the number of sea turtles captured in tow i (in total and per species), Ei is the standardized effort of tow i (30.5 m net hour), n is the sample size (number of tows sampled), sCPUE is the standard error of the CPUE estimated and X is the mean size of the effort unit in the sample (mean duration of a tow in hours). Although the catch of turtles in each tow was not normally distributed, the estimated means can be assumed to have a normal distribution given such a large sample (Poiner & Harris, 1996).

Significant differences between standardized CPUE for licensed shrimp and demersal fish trawlers in each tow were assessed by the Mann–Whitney–Wilcoxon test. The direct initial mortality rate (M) ± 95% CI was estimated according to Alió et al. (2010), based on individuals retrieved dead, since indirect or after-release mortality was not assessed:

$$M = p \pm 1.96\sqrt{\frac{p(100-p)}{n}}$$

where p is the estimated ratio of mortality (number of dead sea turtles/n × 100) and n is the total number of sea turtles captured.

Generalized Linear Models (GLMs) were used to verify which variables influenced the bycatch and the direct initial mortality of sea turtles in double-rig-bottom trawling. The presence–absence of sea turtles bycatch per species in each tow (independent of the fishery target species) was included as a response variable as a function of six fixed explanatory variables: (i) beginning of each tow (hours in decimal format); (ii) tow duration (from trawl net set to retieval in each tow; decimal hours); (iii) water depth of gear deployment (metres); (iv) latitude; (v) longitude, both recorded at the beginning of each tow (decimal degrees); and (vi) season (summer, autumn, winter or spring). One sea turtle not identified at species level was removed from this analysis. The presence–absence of dead sea turtles (any species) in every tow with observed sea turtle bycatch was included as a response variable as a function of two fixed explanatory variables: (i) tow duration (decimal hours); and (ii) water depth of gear deployment (metres).

The models were constructed from different combinations of variables found in the global models (models with all explanatory variables included), using the binomial distribution. The selected models were those whose difference between the second-order corrected Akaike's Information Criterion (AICc) of the model in question and the model with the lowest AICc value was 0–2 ($\Delta\mathrm{AICc} \leq 2$), being considered the estimated parameters of the Binomial Generalized Linear Model-averaged (Burnham & Anderson, 2002). The importance value for each fixed explanatory variable was calculated as the sum of the Akaike weights on the selected models that included that variable (Burnham & Anderson, 2002).

All statistical analyses were computed in program R 3.1.1 (R Core Team, 2017).

3 | RESULTS

A total of 9362 tows were recorded during 186 fishing trips, totalling 43657.52 trawling hours (Table 2). Fishing trips lasted between 3 and 27 days (mean ± SD = 13.5 ± 3.4 days), involving from 10 to 107 tows per trip (mean ± SD = 50.3 ± 16.3 tows/trip). Tow duration ranged between 1.00 and 13.50 h (mean ± SD = 4.66 ± 0.94 h). The total fishing effort did not differ significantly between seasons (H = 0.66, d.f. = 3, p = 0.88). During autumn, the mean depth of the tows was greater (Table 2).

Of the recorded tows, 86.82% were carried out by vessels licensed to catch shrimp/bycatch of marketable species (Table 2). However, these trawlers and those targeting demersal fish concentrated their efforts on the same fishing areas (Figure 1), although shrimp trawlers extended to greater depths (Table 2).

A total of 201 sea turtles were incidentally captured: 52.2% were *C. caretta*, 38.8% were *L. olivacea*, 5.5% were *C. mydas*, 3.0% were *D. coriacea* and one (0.5%), belonging to the family Cheloniidae, without species confirmation (Table 3). The CCL of *C. caretta* individuals (n = 97) varied from 31 to 120 cm (mean ± SD = 84.99 ± 16.64 cm), composed of 58.8% subadults/adults and 41.2% juveniles. The CCL of *L. olivacea* individuals (n = 76) varied from 26 to 79 cm (mean ± SD = 62.04 ± 9.03 cm), being 69.74% subadults/adults and 30.26% juveniles. For *C. mydas* (n = 10), the CCL varied from 29 to 60 cm (mean ± SD = 37.50 ± 8.71 cm), all juveniles. For *D. coriacea* (n = 6), the CCL ranged from 137 to 170 cm (mean ± SD = 148.50 ± 10.34 cm), with 83.33% subadults/adults and one (16.67%) juvenile.

The sex ratio of *C. caretta* (n = 45) was 1.50 females to 1 male. For *L. olivacea* (n = 29), it was 13.50 females to 1 male, and only three individuals of *D. coriacea* had the sex determined, all being males.

Based on the total number of recorded tows, CPUE was 0.02 turtles per tow and the standardized CPUE was 0.0025 turtles h^{-1} ± 0.0032 95% CI. During winter, the CPUE increased (Table 2). The standardized CPUE of shrimp and demersal fish trawlers did not differ significantly (W = 5046900, p = 0.14). Among the sea turtle species, *C. caretta* and *L. olivacea* presented the highest standardized CPUEs (Table 3).

A total of 14 individuals (11 *C. caretta*, one *D. coriacea*, one *L. olivacea* and one Cheloniidae) were retrieved dead by the shrimp trawlers (Figure 2a) and the direct initial mortality rate ± 95% CI was 7.65 ± 3.85%. No dead individuals were recorded by the demersal fish trawler, which caused a decrease in this rate when considering trawling as a whole (Table 2). The mean depth and tow duration ± SD at which sea turtle mortality occurred were 66.43 ± 27.38 m (range = 40–120) and 4.46 ± 1.04 h (range = 2.83–6.50), respectively.

Of the dead individuals, 10 (71.43%) (seven *C. caretta*, one *D. coriacea*, one *L. olivacea*, 1 Cheloniidae) were tagged with numbered

TABLE 2 Summary of the industrial double-rig-bottom trawling effort and sea turtle bycatch in south-eastern Brazil per target species of trawlers, season (2015–2018) and total.

Trawling effort and sea turtles bycatch	Target species		Season				Total
	Shrimp trawlers	Demersal fish trawler	Summer	Autumn	Winter	Spring	
Number of fishing trips	157	29	52	33	50	51	186
Number of tows	8128	1234	2420	1427	2637	2878	9362
Mean duration of a tow ± SD (h)	4.56 ± 0.84	5.31 ± 1.25	4.65 ± 0.89	4.97 ± 0.83	4.57 ± 0.89	4.61 ± 1.02	4.66 ± 0.94
Min–max duration of a tow (h)	1.00–11.50	1.50–13.50	1.50–11.50	1.50–11.50	1.50–9.83	1.00–13.50	1.00–13.50
Total duration of the tows (h)	37103.02	6554.50	11245.55	7096.50	12048.55	13266.92	43657.52
E (standard net hour)	68123.57	12034.49	20647.57	13029.64	22121.93	24358.93	80158.06
Mean depth of a tow ± SD (m)	67.00 ± 24.10	66.07 ± 15.34	65.13 ± 21.48	98.53 ± 20.93	59.15 ± 15.82	59.74 ± 17.43	66.87 ± 23.14
Min–max depth of a tow (m)	20–164	36–119	20–164	40–134	35–130	30–125	20–164
Number of sea turtles bycatch	183	18	39	15	95	52	201
Standardized CPUE ± 95% CI (turtles h^{-1} standard net)	0.0027 ± 0.0034	0.0015 ± 0.0028	0.0019 ± 0.0030	0.0012 ± 0.0022	0.0043 ± 0.0060	0.0021 ± 0.0033	0.0025 ± 0.0032
Number of dead sea turtles	14	0	2	2	9	1	14
Direct mortality ratio ± 95% CI (%)	7.65 ± 3.85	0	5.13 ± 6.92	13.33 ± 17.20	9.47 ± 5.89	1.92 ± 3.73	6.97 ± 3.52

SD, Standard deviation; *E*, standardized effort; CPUE, catch per unit of effort; 95% CI, 95% Confidence intervals.

plastic seals and returned to the sea (Figure 2ab). There was no record of these dead/tagged animals among the strandings recorded by the BMPs.

Five GLM models (ΔAICc ≤ 2) were selected to explain the bycatch of *C. caretta*, 10 for *L. olivacea*, five for *C. mydas* and six for *D. coriacea* in the industrial double-rig-bottom trawling and three for mortality of sea turtles in this fishery, using the average of these models (Table 4). According to the estimated parameters of the model-average, the occurrence of *C. caretta* bycatch was significantly higher during winter, negatively affected by the latitude and positively affected by the longitude (Table 5). The occurrence of *L. olivacea* bycatch was positively affected by the latitude, while for *C. mydas* and *D. coriacea* no variable was significant (Table 5). The direct initial mortality of sea turtles in this fishery was not significantly affected by the trawling duration or depth (Table 5).

4 | DISCUSSION

The present study investigated a limited number of vessels, corresponding to approximately 10% of the total licensed fleet of industrial double-rig-bottom trawlers registered in the state of Rio de Janeiro in 2015 (total of 82 vessels, data from the Brazilian Ministry of Fishery and Aquaculture apud Martins, 2017). Therefore, these results of fishing effort and sea turtles bycatch should be interpreted as minimal estimates in south-eastern Brazil. The monitored trawlers operations were concentrated along the coast of Rio de Janeiro, as this region is closer to their fishing port. The same was reported in a previous study (Guimarães et al., 2018), although in the current study the tows extended to areas further to the south and were also in deeper waters.

According to Martins (2017), the industrial double-rig-bottom trawling registered in the state of Rio de Janeiro has at least two fleets defined by the catch composition and trawling depth: one operates along Rio de Janeiro inner and middle shelf areas (< 100 m), primarily targeting seasonal pink-shrimp, associated with shrimp licensing (MPA/MMA Normative Instruction No. 10 of 2011); and the other operates more to the south of the state, mainly along middle and outer shelf areas (100–250 m), primarily targeting demersal fish, associated with demersal fish licensing (MPA/MMA Normative Instruction No. 10 of 2011). However, both fleets catch shrimp and demersal fishes. In this study, both shrimp and demersal fish trawlers operated mainly in areas up to 100 m deep.

The shrimp fishery in south-eastern Brazil is closed annually from March to May in the austral autumn (IBAMA Normative Instruction No. 189 of 2008), but licensed shrimp double-rig-bottom trawlers have additional authorization during this period to operate outside areas encompassing the distribution of pink-shrimp (>100 m depth), exploring other demersal resources (e.g. *Metanephrops rubellus*) (MPA/MMA Normative Instruction No. 10 of 2011). Therefore, shrimp trawlers continued to fish during the autumn mainly in deeper waters, with 6.5% of the tows occurring illegally in waters <100 m deep. The demersal fish trawler continued to operate mainly in areas up to 100 m deep. However, some trawlers interrupted their fishing

TABLE 3 Number and standardized CPUE ± 95% CI (in parentheses) of sea turtles bycaught in shrimp and demersal fish double-rig-bottom trawlers per species and total, minimum, maximum, mean and standard deviation of catch depths (m) in south-eastern Brazil (2015–2018).

	Number of bycatch (standardized CPUE ± 95% CI; turtles h^{-1} standard net)			Water depth (m)	
Species	Shrimp trawlers	Demersal fish trawler	Total	Min–max	Mean ± SD
Caretta caretta	89 (0.0013 ± 0.0021)	16 (0.0013 ± 0.0026)	105 (0.0013 ± 0.0020)	38–128	65.42 ± 22.58
Lepidochelys olivacea	76 (0.0011 ± 0.0019)	2 (0.0002 ± 0.0014)	78 (0.0010 ± 0.0016)	35–119	55.24 ± 21.43
Chelonia mydas	11 (0.0002 ± 0.0009)	0	11 (0.0001 ± 0.0008)	38–70	52.82 ± 9.42
Dermochelys coriacea	6 (0.0001 ± 0.0008)	0	6 (0.0001 ± 0.0007)	38–90	53.83 ± 17.71
Total[a]	183	18	201	35–128	60.36 ± 22.07

[a]One individual with unconfirmed species.

TABLE 4 The selected Binomial Generalized Linear Models (ΔAICc ≤ 2) for sea turtle bycatch and mortality by the industrial double-rig-bottom trawl fishery as functions of explanatory variables in south-eastern Brazil.

Variable response	Selected models	AICc	ΔAICc	*w*
Caretta caretta bycatch	Season + hour + latitude + longitude	1095.57	0.00	0.33
	Tow duration + season + hour + latitude + longitude	1096.06	0.49	0.26
	Season + latitude + longitude	1097.30	1.73	0.14
	Tow duration + season + latitude + longitude	1097.32	1.75	0.14
	Season + hour + latitude + longitude + water depth	1097.56	1.98	0.12
Lepidochelys olivacea bycatch	Latitude + water depth	856.82	0.00	0.17
	Latitude	857.27	0.45	0.14
	Latitude + longitude	857.50	0.67	0.12
	Hour + latitude + water depth	857.70	0.88	0.11
	Tow duration + latitude + water depth	857.99	1.17	0.10
	Hour + latitude	858.23	1.40	0.08
	Hour + latitude + longitude	858.42	1.60	0.08
	Latitude + longitude + water depth	858.57	1.75	0.07
	Tow duration + latitude + longitude	858.70	1.88	0.07
	Tow duration + latitude	858.70	1.88	0.07
Chelonia mydas bycatch	Tow duration + water depth	167.50	0.00	0.34
	Tow duration	168.67	1.17	0.19
	Tow duration + latitude + water depth	168.87	1.37	0.17
	Tow duration + longitude + water depth	168.92	1.42	0.17
	Water depth	169.29	1.79	0.14
Dermochelys coriacea bycatch	Season	98.60	0.00	0.27
	Season + latitude	99.24	0.64	0.20
	Season + longitude	99.29	0.69	0.19
	Season + water depth	99.84	1.23	0.15
	Tow duration + season	100.59	1.99	0.10
	Season + hour	100.59	1.99	0.10
Sea turtle mortality	1	101.52	0.00	0.48
	Tow duration	102.73	1.21	0.26
	Water depth	102.76	1.23	0.26

AICc, Second-order corrected Akaike Information Criterion; *w*, Akaike weights.

activities during most of the closed shrimp season to make major repairs and/or renovations.

Bycatch of *C. caretta* subadults/adults was the most common, followed by *L. olivacea* subadults/adults, supporting the findings of a previous study in this region (Guimarães et al., 2018). *C. caretta* has been reported to be the species most often incidentally captured by trawling in Southern Brazil (Guterres et al., 2014; Monteiro et al., 2013; Monteiro et al., 2016), Uruguay (Laporta, Miller, & Domingo, 2013), the Atlantic coast of the USA (Epperly et al., 1995; Henwood & Stuntz, 1987; Murray, 2008), north Adriatic Sea and Italy (Casale et al., 2004), the Mediterranean Sea (Casale, Cattarino, Freggi, Rocco, & Argano, 2007; Lucchetti & Sala, 2010), Gulf of Gabès, Tunisia (Jribi, Bradai, & Bouain, 2007) and eastern Spain (Domenech et al., 2013).

Caretta caretta is the most common species to nest along the continental Brazilian coast, with beaches from northern Rio de Janeiro and Espírito Santo forming one of its primary rookeries in Brazil (Lima, Wanderlinde, Almeida, Lopez, & Goldberg, 2012; Marcovaldi & Marcovaldi, 1999). The proximity of nesting beaches may help explain

TABLE 5 Estimated parameters of the Binomial Generalized Linear Model averaged for sea turtle bycatch and mortality by the industrial double-rig-bottom trawl fishery as functions of explanatory variables in south-eastern Brazil.

Variable response	Model-averaged coefficients	Estimate	2.5% CI	97.5% CI	*Z*-Value	*P*-Value	Importance
Caretta caretta bycatch	Intercept	−1.12	−10.13	7.89	0.24	0.808	—
	Season (spring)	−0.08	−0.89	0.73	0.20	0.845	1
	Season (summer)	0.27	−0.50	1.05	0.69	0.491	1
	Season (winter)	**0.97**	**0.23**	**1.71**	**2.56**	**0.011**	**1**
	Latitude	**−0.89**	**−1.69**	**−0.10**	**2.21**	**0.027**	**1**
	Longitude	**0.58**	**0.23**	**0.92**	**3.24**	**0.001**	**1**
	Hour	−0.03	−0.05	0.001	1.88	0.061	0.72
	Tow duration	0.13	−0.06	0.33	1.33	0.184	0.40
	Water depth	−0.001	−0.02	0.01	0.14	0.891	0.12
Lepidochelys olivacea bycatch	Intercept	20.11	7.10	33.11	3.03	0.002	—
	Latitude	**1.25**	**0.15**	**2.35**	**2.23**	**0.026**	**1**
	Water depth	−0.01	−0.03	0.005	1.42	0.155	0.45
	Longitude	−0.29	−0.81	0.23	1.08	0.279	0.34
	Hour	−0.02	−0.05	0.01	1.04	0.298	0.27
	Tow duration	0.10	−0.12	0.31	0.88	0.378	0.23
Chelonia mydas bycatch	Intercept	−5.36	−21.18	10.46	0.66	0.507	—
	Tow duration	−0.77	−1.55	0.01	1.94	0.052	0.86
	Water depth	−0.04	−0.08	0.01	1.65	0.099	0.81
	Latitude	−0.49	−1.69	0.70	0.81	0.419	0.17
	Longitude	−0.18	−0.62	0.27	0.77	0.440	0.17
Dermochelys coriacea bycatch	Intercept	−15.69	−4111.05	4079.68	0.01	0.994	—
	Season (spring)	15.24	−4080.02	4110.51	0.01	0.994	1
	Season (summer)	−0.24	−5165.37	5164.90	0.00	1.000	1
	Season (winter)	16.96	−4078.31	4112.23	0.01	0.994	1
	Latitude	0.91	−0.65	2.47	1.14	0.254	0.20
	Longitude	0.40	−0.33	1.14	1.08	0.282	0.19
	Water depth	−0.03	−0.09	0.04	0.82	0.412	0.15
	Tow duration	−0.06	−0.96	0.84	0.13	0.898	0.10
	Hour	0.01	−0.11	0.12	0.11	0.915	0.10
Sea turtle mortality	Intercept	−2.36	−4.52	−0.20	2.15	0.032	—
	Tow duration	−0.27	−0.88	0.34	0.86	0.389	0.26
	Water depth	0.01	−0.01	0.03	0.92	0.359	0.26

Significant variables ($P < 0.05$) are marked in bold.

the high rate of subadult/adult bycatch of this species in the study area, as previously suggested by Guimarães et al. (2018). In addition, *C. caretta* subadults and adults prefer neritic habits, foraging near the bottom (Barceló et al., 2013; Monteiro, 2017), where this fishery operates. The large volume of bycatch discarded by trawls may also attract sea turtles (Beneditto, Moura, & Siciliano, 2015; Tomas, Aznar, & Raga, 2001), creating a high density of turtles in areas being actively fished, thereby increasing the rates of turtle bycatch (Shoop & Ruckdeschel, 1982). Therefore, considering the biological value of females and males in reproductive activity, nest protection alone is insufficient to offset adult sea turtle mortality from incidental captures in waters near nesting grounds.

High levels of *L. olivacea* bycatch in bottom trawls have been reported in a few areas: Gabon (Casale et al., 2017), Pacific Costa Rica (Arauz, Vargas, Naranjo, & Gamboa, 1997) and the Orissa coast in India (Gopi, Pandav, & Choudhury, 2007). In the latter two regions, reproductively active adults congregate annually in the coastal waters off nesting beaches, which may contribute to increased bycatch rates. In Sergipe, the main nesting location for *L. olivacea* in Brazil, shrimp trawling is considered the main threat to reproductive females (Castilhos, 2016; Silva et al., 2007; Silva et al., 2010). The relatively high rate of *L. olivacea* bycatch in bottom trawlers in Rio de Janeiro, however, cannot be explained by proximity to Sergipe, as it is more than 1500 km away. However, females probably migrate to this area to take advantage of the abundant prey, as suggested by other authors (Beneditto et al., 2015; Guimarães et al., 2018; Reis et al., 2009; Reis, Pereira, et al., 2010; Reis et al., 2017).

In the present study, the occurrence of *C. caretta* bycatch was significantly higher during winter, at lower latitudes (−24° to −23°) and higher longitudes (−42° to −40°) while the *L. olivacea* bycatch was significantly higher at higher latitudes (−23° to −21°). Although the coastal upwelling is more intense during the late spring and summer mainly owing to wind-driven forces, the abrupt change in the coastline orientation of Rio de Janeiro state (23° S 42° W) induces the cyclonic meandering of the Brazil Current in this region, that also forces the pumping of South Atlantic Central Water from the deeper region onto the continental shelf, resulting in high productivity throughout the year (Campos, Velhote, & Silveira, 2000). Further north of the state, there is the mouth of a large river, the Paraíba do Sul river (~22°S), which also contributes a great amount of organic matter entering the coastal zone (Souza & Knoppers, 2003). These factors therefore may contribute to the existence of an enhanced feeding zone for sea turtles in this region, as suggested by other authors (Reis, Pereira, et al., 2010; Reis et al., 2017; Reis, Moura, Lima, Rennó, & Siciliano, 2010; Reis et al., 2009), and thus explain the greater occurrence of *C. caretta* and *L. olivacea* bycatch in these areas. The bottom-dwelling prey of these species (Beneditto et al., 2015) overlaps with the occurrence of the target catch of the bottom trawls.

In general, during winter the sea is rougher (Klumb-Oliveira, Pereira, & Leão, 2015; Souza, Bulhões, & Amorim, 2015), which may cause the turtles to remain longer near the bottom, and thus more vulnerable to capture by bottom trawls. This may explain the higher occurrence of *C. caretta* bycatch and total CPUE recorded in winter.

The bycatch of *C. mydas* in the bottom trawl fishery, although relatively small, was expected because it is the most commonly encountered non-reproductive species along the Brazilian coast (Santos et al., 2011). It has been reported as incidentally captured by trawling in Southern Brazil (Guterres et al., 2014; Monteiro et al., 2013) and in almost all other reported areas in the world (Alió et al., 2010; Arauz et al., 1997; Casale et al., 2017; Epperly et al., 1995; Henwood & Stuntz, 1987; Laporta et al., 2013; Poiner & Harris, 1996; Robins, 1995). However, its relatively infrequent rate of incidental capture by bottom trawls may reflect its preference for shallower waters when in coastal areas (Almeida, Santos, et al., 2011). However, smaller *C. mydas* tend to remain in deeper oceanic waters (Bjorndal, 1996), only moving into more coastal environments after they reach between 30 and 40 cm CCL (Balazs, 1995).

This is the first record of *D. coriacea* bycatch in trawls operating in south-eastern Brazil. Incidental capture of this species was previously reported in bottom trawling in the far south of the country (Guterres et al., 2014), north-eastern Venezuela (Alió et al., 2010), Uruguay (Laporta et al., 2013) and Gabon (Casale et al., 2017). Its relatively low rate of bycatch in this fishery is probably associated with its preference for pelagic habitats (Almeida, Eckert, et al., 2011; Thomé et al., 2007). Brazil has one of the smallest nesting populations of *D. coriacea* in the world, located on the northern coast of Espírito Santo (Thomé et al., 2007). However, on the other side of the Atlantic, Gabon has one of the largest nesting populations of this species (Witt et al., 2009). It is known that females that nested in Gabon will cross the Atlantic, migrating through the waters of Brazil, Uruguay and Argentina (Billes et al., 2006; Fossette et al., 2010; Witt et al., 2011). Therefore, it is possible that Brazilian bottom trawlers are capturing animals from the Eastern Atlantic, but genetic studies are necessary to test this hypothesis.

Although the effort in this study (80,158.06 h standard net) was five times higher than that analysed by Guimarães et al. (2018) in the same region (15,263 h standard net), the estimated CPUE was similar (0.0025 turtles h^{-1} ± 0.0032 95% CI standard net vs 0.0029 turtles h^{-1} ± 0.004 95% CI standard net). In addition, Guimarães et al. (2018) monitored fewer trawlers, suggesting that CPUE was also maintained when considering a larger portion of the industrial double-rig-bottom trawl fleet operating in south-eastern Brazil. Considering the results of this study, where vessels make an average of two trips per month, 50 tows per trip, fish during 12 months of the year and catch 0.02 turtles per tow, it is estimated that 24 turtles are incidentally caught per year by each trawler in this region. By applying this rate to the total fleet of industrial double-rig-bottom trawlers registered in Rio de Janeiro state (82 vessels, data from the Brazilian Ministry of Fishery and Aquaculture apud Martins, 2017), it is estimated that 1968 turtles are caught per year. However, bottom trawling in south-eastern Brazil also includes artisanal vessels and industrial vessels registered in other states.

The CPUE estimated was lower than the CPUE reported for trawling in southern Brazil (Guterres et al., 2014: 0.05 turtles/tow; Monteiro et al., 2013: 0.14 turtles/tow). It was also one of the lowest recorded anywhere, with CPUE varying from 0.0031 to 0.1019 turtles h^{-1} standard net (Arauz et al., 1997; Casale et al., 2004; Casale et al., 2007; Henwood & Stuntz, 1987; Jribi et al., 2007; Poiner & Harris, 1996; Robins, 1995), higher only than that estimated for north-eastern Venezuela (0.0011 ± 0.0003 turtles h^{-1} standard net, Alió et al., 2010). This may indicate that bottom trawling represents a lesser threat to sea turtles in the study area compared with these other regions. However, more studies that monitor the various trawl fleets operating in south-eastern Brazil including on-board observers are needed to better contextualize our results.

Even considering that trust was built between the researchers and collaborating captains, under-reporting of mortality could still have occurred, as captains may have been concerned about possible penalties detailed in the Brazilian legislation. However, the direct initial mortality rate (7.65 ± 3.85%) in this study was within the range (3.3–9.4%) recorded by some studies using on-board observers (Casale et al., 2004, 2017; Jribi et al., 2007), suggesting that self-reporting may be adequate when on-board observer information is lacking, especially when research funds are limited (Guimarães et al., 2018; Poiner & Harris, 1996; Robins, 1995).

The tow duration is considered a critical parameter for survival of sea turtles incidentally caught by trawling (Casale et al., 2007; Henwood & Stuntz, 1987; Lucchetti & Sala, 2010). In this study, mean tow duration (4.66 ± 0.94 h) was higher than that reported for other regions, which ranged from 1.21 to 3.25 h (Alió et al., 2010; Casale et al., 2004, 2017; Gopi et al., 2007; Henwood & Stuntz, 1987; Jribi et al., 2007). This is a worrying factor for the study area; however, no significant relationship between tow duration and direct initial mortality rates of sea turtles was found in this study and long tow times did not result in overall high rates of mortality. The time a turtle was caught in a long-duration tow, although unknown, may also be a relevant factor for the mortality of these animals, as a turtle caught shortly before the end of the tow has a much better chance of survival (Fahlman, Crespo-Picazo, Sterba-Boatwright, Stacy, & Garcia-Parraga, 2017; Sasso & Epperly, 2006).

Sea turtles are suspectible to decompression sickness and gas embolism when retrieved quickly from depths >10 m, with an increased likelihood of delayed mortality from this condition (Fahlman et al., 2017; García-Párraga et al., 2014). The occurrence of these conditions in the incidentally captured turtles was not assessed, nor were the released turtles followed, to check on delayed mortality. In this study, all tows with incidentally captured turtles occurred at depths >10 m and 17.91% occurred at depths >80 m, raising the possibility that some turtles may have experienced decompression sickness and/or gas embolism, with delayed mortality after being released alive from the trawls. Future studies on this issue are needed for a more accurate estimate of sea turtle mortality rates in bottom trawling as well as to plan efforts to avoid or minimize the harmful effects of bycatch (Fahlman et al., 2017).

As no tagged turtle carcasses from the trawlers were observed stranded on the coast of Rio de Janeiro state, it was impossible to link data on stranded turtles with bycatch rates. However, this does not mean that the relationship does not exist, as the strandings are influenced by several variable factors, including ocean currents, winds, predators and necrophagous species, which can prevent the carcasses from stranding on beaches (Hart, Mooreside, & Crowder, 2006; Koch, Peckham, Mancini, & Eguchi, 2013; Tomás et al., 2008). Indeed, observed stranded turtles are thought to represent only a small part of the total sea turtle mortality in the ocean (Hart et al., 2006; Koch et al., 2013).

Others have reported that tagged turtle carcasses released from bottom trawlers operating in the south-west Atlantic were subsequently observed stranded on the coast: 30% in a study in Southern Brazil (unpublished data *apud* Monteiro et al., 2016) and at least 25% in Uruguay (Miller, Laporta, Domingo, Lezama, & Rios, 2006). However, those studies monitored fisheries that occurred at depths between 10 and 50 m, and most of the sea turtle bycatch occurred in <20 m water depth, closer to the shoreline (Laporta et al., 2013; Miller et al., 2006; Monteiro et al., 2013). In the current study, the bottom trawls fished in deeper waters further away from the coast, making it less likely that turtle carcasses would reach the shoreline. Furthermore, although the number of tagged turtle carcasses from the trawlers was small, there is also the possibility that BMPs failed to find and marked stranded turtles because of logistical constraints or other causes. We recommend that any future implementation of fisheries monitoring programmes include not only on-board observers, but also well-staffed and standardized BMPs to identify the relationships between bycatch and occurrence of stranded turtles.

In the late 1990s, the south-eastern southern Brazil trawler fleet became highly opportunistic and multispecific following the overexploitation and reduced catch rates of traditional demersal resources, such as pink-shrimp (Martins, 2017; Pezzuto & Benincà, 2015). Bottom trawling is an unselective fishing method, and the current management system in Brazil allows this gear to be used over a large area with high marine biodiversity. This results in the capture of many species other than the primary targets of shrimp and demersal fishes (Pezzuto & Benincà, 2015). According to Pezzuto and Benincà (2015), the current licensing system encourages excessive effort concentrated in a region with limited fishing resources. Some authors suggest that licensing should move from a species-based to a spatial and seasonal-based approach, by defining smaller management areas according to their species assemblages, bottom characteristics, depth, fleet dynamics and technical considerations, where fleets would be allowed to operate only within one or a few units, following specific management measures (Martins, 2017; Perez et al., 2001; Pezzuto & Benincà, 2015; Rosso & Pezzuto, 2016).

In Brazil, a national law passed in 1994 made it mandatory for TEDs to be installed on shrimp trawls (IBAMA Ordinance No. 36 of 1994), to reduce bycatch of sea turtles and allow shrimp to be exported to the USA. However, in south-eastern southern Brazil, inspection and enforcement of this requirement is irregular, leading to infrequent use through either lack of awareness or neglect (Guimarães et al., 2018; Silva, 2015; Silva et al., 2010). The requirement for mandatory use of TEDs in Brazil includes only trawlers >11 m with shrimp licences (MMA Normative Instruction No. 31 of 2004). In the current study, the trawlers with shrimp and demersal fish licences used nets with similar size and mesh, concentrating their efforts in the same fishing area, as also reported by other authors (Pezzuto & Benincà, 2015; Queirolo, Wahrlich, Molina, Munari-Faccin, & Pezzuto, 2016), and their estimates of sea turtle bycatch CPUE did not differ significantly. Furthermore, shrimp trawlers are licensed to incidentally catch larger commercial species that would normally be excluded by TEDs, and this has been used as a justification by shipowners to avoid using TEDs (Silva, 2015). A recent experiment on the effectiveness of two different configurations of TEDs in Brazilian shrimp trawlers reported that a top-opening model did not significantly reduce catch rates of target species (Schroeder, Bottene, Sant'Ana, Wahrlich, & Queirolo, 2016). More testing of available TED configurations is needed to help ensure that TEDs will be accepted by the trawl fleets. We also suggest that other mitigation measures should be adopted to reduce bycatch and mortality of sea turtles in demersal fish trawlers and boats <11 m, not included in the TED requirement, for example, the development of a TED with greater spacing and adapted to the Brazilian fishing conditions.

Another potential management action to reduce bycatch in the bottom trawl fishery is a spatial/seasonal-based approach in the management of bottom trawling in south-eastern–southern Brazil (Martins, 2017; Perez et al., 2001; Pezzuto & Benincà, 2015; Rosso & Pezzuto, 2016). Developing solutions to the problem of sea turtle bycatch and mortality in this fishery is challenging, considering the biological, economic, social, structural, legal and operational complexities of fishing. However, more studies similar to this will help further elucidate the different components and their interactions in this issue, which will help inform management measures to reduce bycatch and maintain fisheries.

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