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Cumulative threats to juvenile green turtles in the coastal waters of southern and southeastern Brazil

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Abstract
Management of marine turtles at broad spatial scales is challenging due to the costs and the logistical feasibility of collecting ecological data and information on multiple threats at this scale. Spatially explicit assessments of the exposure of marine turtles to cumulative threats provides an alternative approach by identifying regions that are impacted by multiple threats at broad scales. To inform future management of juvenile green turtles, *Chelonia mydas,* off the southern and southeastern Brazilian coast we determined their cumulative exposure to five pertinent anthropogenic activities (marine traffic, port areas, and artisanal, trawl and gillnet fisheries). Information on the spatial distribution of juvenile green turtles was obtained by satellite tagging 14 wild-caught turtles in the Paranaguá Estuarine Complex, off the Paraná coast in southern Brazil and human activity information was obtained from various databases. This allowed us to identify the anthropogenic activities that provide the greatest risk to marine turtles (artisanal fisheries and marine traffic) and five "hotspot" threat areas that require prompt local management intervention to protect marine turtles in the region. These results can be used to inform on the ground efforts where further impact assessments and management interventions can be prioritized and undertaken.

Keywords Marine turtles · *Chelonia mydas* · Exposure · Human pressure · Foraging · Displacement

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Introduction

The protection and management of species of conservation concern requires knowledge of their spatio-temporal distribution, migratory and space-use patterns, and how these parameters influence their exposure to different threats (Gredzens et al. 2014; Wildermann et al. 2018b). Satelitte tracking species of conservation concern can provide the needed information to aid protection and management (Bograd et al. 2010; Cooke 2008; Fuentes et al. 2019). Multiple populations of marine turtles are threathened and as a response, several efforts have been undertaken to determine their specific exposure to anthropogenic threats (Mazaris et al. 2017; Wallace et al. 2011a, b). All seven species of marine turtles have complex life cycles, using terrestrial and marine environments throughout different life stages during which they are exposed to an array of threats, that require mitigation at multiple levels (Bolten et al. 2011; Fuentes et al. 2015; Klein et al. 2016).

In the context of limited resources, managers need to prioritize their time, available funds and efforts for effective conservation (Fuentes et al. 2015; Klein et al. 2016). For this reason, it is necessary to understand the spatial extent, magnitude and relative impact of key threats, as well as to identify areas, that if protected, would provide the most conservation benefit (Joseph et al. 2009). The latter requires spatial knowledge of the cumulative threats to a given species. However, for marine turtles, most studies often focus on isolated threats at a particular time and location (Katselidis et al. 2013; Schofield et al. 2013). Relatively few studies have investigated cumulative, synergistic and secondary effects of different activities across a broad spatial scale [e.g., Fuentes and Hamann (2011), Lewison et al. (2014) and Wallace et al. (2011a); but see recent paper by Hart et al. (2018)].

Juvenile green turtles (*Chelonia mydas*) using coastal waters are exposed to multiple threats, including ports and their associated activities, urban/tourism or unplanned development and associated pollution, or small-scale, industrial and recreational fisheries (Colferai et al. 2017; Domiciano et al. 2017; Gallo et al. 2006; Guebert-Bartholo et al. 2011; Hart et al. 2018; Pierri et al. 2006; Shaver et al. 2013; Silva et al. 2017; Wildermann et al. 2018b). The southern and southeastern Brazilian coast provides important foraging and developmental habitats for marine turtles, especially the Endangered green turtle(Fernandes et al. 2017; Gallo et al. 2006; Gama et al. 2016; Guebert-Bartholo et al. 2011; Nagaoka et al. 2012), with more than 10,000 individuals washed on land stranded in the region during the last three years (2016–2019) (SIMBA 2019). While regional impacts to sea turtles in Brazil have been identified, limited information exists on the effects of the cumulative exposure of juvenile green turtles to the multitude of threats they experience in this region (Wildermann et al. 2018a), with studies focusing mainly on the direct exposure to fisheries interactions and plastic ingestion, from stranding events or from onboard observers (Bugoni et al. 2001; Gama et al. 2016; Kotas et al. 2004; Sales et al. 2008; Santos et al. 2015).

Marine turtles at foraging grounds of the southwestern Atlantic Ocean may be resident to specific areas, or more transitory, moving large distances (> 1000 km) in search of resources and/or optimal environmental conditions (Carman et al. 2012; Godley et al. 2003; Torezani et al. 2009; Vélez-Rubio et al. 2018). Transient turtles, as they migrate large distances, are likely exposed to a higher diversity of threats and cumulative stressors than those that remain resident in some areas. Consequently, beyond determining exposure to multiple threats at foraging areas, it is also important to consider threats to migratory corridors, which are areas used by turtles while moving between foraging areas (Carman et al. 2012; Pendoley et al. 2014; Vélez-Rubio et al. 2018).

To inform future management and research priorities for juvenile green turtles off the southern and southeastern Brazilian coast, we determined the co-occurrence levels of satellite-tracked turtles, resident and transient individuals, to five pertinent regional threats: marine traffic, port areas, and artisanal, industrial/commercial trawl and gillnet fisheries. This allowed us to identify "hotspot" threat areas that require management to protect marine turtles in the region.

Materials and methods

Study area

The Paraná (PR) and São Paulo (SP) states are part of the southern Brazilian continental shelf, which is influenced by the Brazilian Current (flows from north to the south), and by the regional Falkland Current as well as estuarine out-flows (Heileman and Gasalla 2008) (Fig. 1). The geomorphology and the oceanographic dynamics of the region are both responsible for the highly productive waters and the occurrence of a marine biodiversity hotspot (Lana et al. 2001). This region is also an important area for artisanal and industrial fisheries and port development, including the two biggest ports in Brazil: port of Santos (in SP) and port of Paranaguá (in PR). These activities and associated pressures (e.g., unplanned urban development, intense marine traffic and the associated chemical and sewage pollution) impact the marine habitat and species in the region (Domiciano et al. 2019; Gama et al. 2016; Trevizani et al. 2019).

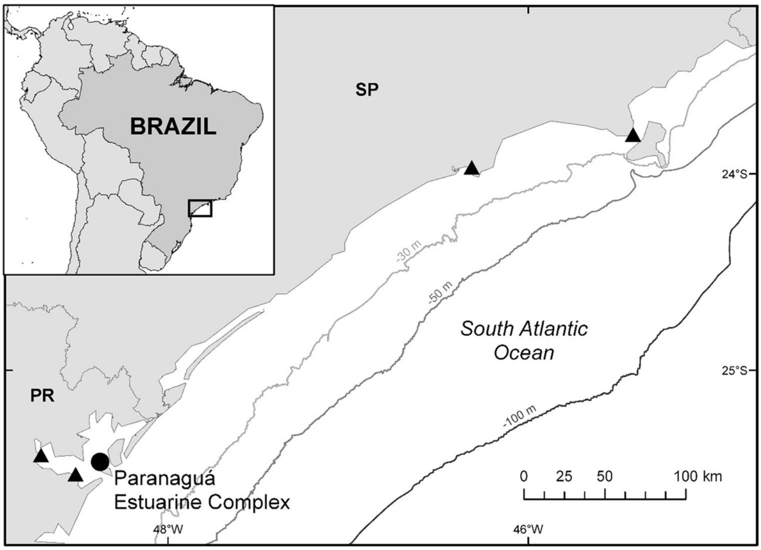

Fig. 1 Study area, release location of satellite tracked juvenile green turtles between 2016 and 2017 (circle) and ports of interest (triangles; from left to right: Antonina port, Paranaguá port, Santos port, São Sebastião port). *PR* Paraná state, *SP* São Paulo state. Depth contours were vectorized from Brazilian nautical charts (available at https://www.marinha.mil.br/chm/dados-do-segnav-cartas-nauticas/cartas-nauticas)

Turtle capture and tracking

Juvenile green sea turtles were captured and tagged in the Paranaguá Estuarine Complex, off the Paraná coast in southern Brazil (Fig. 1), during three field expeditions (from 5th of May to 1st of June in 2016, 28th of September to 3rd of October in 2016, and also 17, 21 and 23th of February and 21th of March in 2017). This region is recognized as an important foraging ground for this species (Andrade et al. 2016; Gama et al. 2016). Turtles were intentionally captured using a surface-set tangle net (50 m in length, 3 m meters in height and 0.30 m in mesh size). The net was set for a period of 2–4 h at a known foraging site and was monitored for signs of turtle or any other by-caught species every 15 to 30 min. When turtles were captured they were immediately brought to the surface, disentangled from the net and transferred to the research vessel (26-foot center console vessel with two 150 Hp engines). Morphometric measurements (using a tape measure, ±0.1 cm) were taken for each turtle, including: curved carapace length (CCL), head width, plastron length and tail length as per protocols described by Balazs (1999). Body weight (±0.1 kg; W) was recorded using a hanging balance (PESOLA AG, PHS100) following protocols described by Balazs (1999). Turtles were also checked for the presence of fibropapillomatosis; only visibly healthy turtles without fibropapillomatosis were considered for satellite tag deployment and were also tagged with two Inconel flipper tags, one on the trailing edge of each front flipper (National Band and Tag Company, Style 681).

A combination of Wildlife Computers (Redmond, WA, USA) Spot-6 platform terminal transmitters (PTTs, hereafter "satellite tags") were deployed on a subset of turtles, with 14 wild-caught juvenile green turtles between 2016 (n = 9) and 2017 (n = 5) being satellite tagged (Table 1). Two different sizes of satellite tags were used (SPOT 311, 51 × 27 × 19 mm and SPOT 287, 70 × 41 × 23 mm) depending on the size of the turtle captured. Satellite tags were attached to the anterior portion of the shell following modified methods by Seney et al. (2010) and recommendations by Jones et al. (2013). In summary, prior to transmitter attachment, the anterior portion of the carapace was sanded with coarse sandpaper (60-grit) and cleaned with acetone to increase bonding strength of the epoxy. A layer of two-part epoxy was applied to the cleaned portion of the carapace and the base of the transmitter. After the epoxy was cured, a steel-reinforced epoxy (Sonic-Weld) was applied over the epoxy and around the base of the transmitter. Antifouling paint (Tempo Marine) was then applied to transmitters before attachment and two coats of a brush on antifouling paint (Interlux Micron Extra) were applied to transmitter non-metal surfaces and epoxies after attachment. Deployment of tags took no longer than 2 h, and turtles were released thereafter. Turtles were tracked within their foraging grounds and along their migrations routes, when applicable.

Turtle space-use layer

We used hierarchical switching state space models (hSSM; Jonsen et al. 2006) to reconstruct the track of each turtle. Switching state space models estimate the behavioral state (e.g. movement and area-restricted use, high- and low-intensity use) of the tracked animals based on the turning angle and autocorrelation between speed and direction, and provides an indication of when an animal switches between behavioral states (Hart et al. 2018; Jonsen et al. 2006, 2007; Patterson et al. 2009; Pedersen et al. 2008). Behavioral estimates range from state 1 to state 2 (unitless), where smaller values represent movement

Table 1 Summary of study turtles, satellite tracking deployment and transmission length for each turtle

Turtle ID	CCL (cm)	Weight (kg)	Type of Spot-6 PTT	Satellite tag deployment date	Total number of transmission days	Total number of transmission days during displacement	Total number of transmission days during foraging
BR95508	42.2	7.5	311B	20-May-16	199	25	174
BR95517	36.5	6.1	311B	22-May-16	72	19.5	52.5
BR95576	34.5	4.6	311B	24-May-16	18	69.5	76.5
BR95599	34.8	9.5	287C	26-May-16	345	28	317
BR95580	31.3	7.1	287C	27-May-16	100	64	36
BRA05251	40.2	7.4	287C	28-Sep-16	14	0	14
BRA05276	35.1	5.0	287C	29-Sep-16	73	0	73
BRA05281	41.1	8.5	287C	1-Oct-16	75	0	75
BRA05284	37.8	5.8	287C	3-Oct-16	60	0	60
BRA05287	40.2	9.8	287C	17-Feb-17	33	0	33
BRA05254	37.1	6.5	311B	21-Feb-17	34	0	34
BRA05257	39.9	7.1	287C	23-Feb-17	77	6	71
BRA05265	44.2	8.5	287C	21-Mar-17	25	0	25
BRA05261	41.0	6.0	311B	21-Mar-17	74	0	74

All turtles were tracked from the Paranáguá Estuarine Complex, Paraná state, Brazil

CCL curved carapace length, *PTT* platform terminal transmitters of individuals and larger values represent area-restricted behaviors (Jonsen et al. 2013). We used a single cut-off of 1.50 to classify movements (as pointed out in Jonsen et al. 2007), so that values from 1 to 1.49 were classified as "moving", which we considered as the movement between foraging areas, and values from 1.50 to 2 were classified as "foraging", which we considered as mostly feeding behavior but could also comprise resting behavior. Estimates closer to 1 or 2 have very low uncertainty, while estimates closer to 1.50 have higher uncertainty; only 2.5% of the reconstructed locations were estimated to have behavioral states between 1.25 and 1.75. The turtle space-use layer were computed using all satellite-derived locations (Advanced Research Global Observation Satellite (ARGOS) location class (LC) 3, 2, 1, 0, A and B, except for Z), and with the following setup: a Markov chain Monte Carlo (MCMC) model was iterated 300,000 times, the first 200,000 iterations were excluded (burn-in), every 100th of the remaining 100,000 iterations was retained, and reconstructed locations were computed at six-hour intervals (Shimada et al. 2016). We removed reconstructed locations that fell within periods with more than five days without raw ARGOS fixes (Bailey et al. 2008). The raw high-quality satellite-derived locations (LC 3, 2, 1) where then added back to the dataset of reconstructed tracks (Shimada et al. 2016; Vincent et al. 2002), and further filtered by removing locations on land.

For each turtle and each behavioral state, filtered locations were normalized by the inverse of its total tracking length (as per Table 1). Normalized locations were used to create raster layers (cell size: 4 km^2) of space-use for each turtle, using the R package *trip* (Sumner 2016). For each behavioral state, we added the normalized space-use rasters using the Cell Statistics tool in ArcMap 10.5.1, and weighted each cell by the number of turtles that occurred in it. We then smoothed the normalized and weighted rasters using the Kernel Density Estimator tool in ArcMap (weight field: time spent column; cell size: 4 km^2; bandwidth: 4 km) to create a layer indicating the areas frequently used by the tracked turtles under each behavioral state. Finally, to create space-use layers of the tracked turtles that were comparable to the human activity layers (see next section) we rescaled the smoothed raster layers (0–1, from no exposure to high exposure; Table S1) using the Fuzzy Membership tool with linear membership in ArcMap 10.5.1. To estimate space-use layers during foraging behavior, we re-scaled the values for each foraging ground independently, so that we could highlight the areas most used by turtles in each foraging ground, and then added the individual re-scaled layer into one final space-use layer using the Cell Statistic Tool in ArcGIS 10.5.1.

Human activity layers—intensity

Marine traffic

Marine traffic navigation areas and routes were obtained from the 2015–2016 global navigation heatmap from the Marine Traffic website (www.marinetraffic.com). Navigation locations were obtained through the vessels' Automatic Identification System (AIS). This dataset included information on all passengers' vessels, as well as all commercial vessels over 299 Gross Tonnage that travel internationally and carry a Class A AIS transponder (which transmits and receives AIS data) aboard (smaller vessels can also be equipped with a Class B AIS transponder). This information was geo-referenced using ground control points at GDAL Geo-referencer in QGIS, with final Root Mean Square (RMS) error less than a half of pixel size (~450 m). The Red Green Blue color space was converted to qualitative densities using the amount of red in the original image as an indicator of density and was rescaled to values between 0 and 1 using a linear function (Table S1).

Ports

To calculate the exposure to ports, we assumed that pressures associated with ports (e.g., pollution, dredging) occurred within a 15 km range of each port, calculated as a conservative measure of the minimum extent of impact of the ports. The location of the ports was used as input to compute a Kernel density estimator (KDE) with the 'KernSmooth' package in R, using a gaussian surface and a 15 km bandwidth. The output layer was a smoothed surface in which exposure to ports decreased with distance from each port. The smoothed layer was rescaled to values between 0 and 1 using a linear function (Table S1).

Artisanal fisheries

Information on artisanal fisheries was obtained from productive units (vessels + fisherman) in the region, determined by interviews with fishermen between July and August 2016 and presented in Petrobras (2017). We rasterized the maps from this work using QGIS 2.18. The maps aggregated data in 5-min grids for each state, with values ranging from zero to 280 fisherman at each grid. The rasterized layer was later rescaled to values between 0 and 1 using a linear function (Table S1).

Industrial trawl and gillnet fisheries

Industrial trawl and gillnet fisheries were determined from kernel density maps provided by the Ministry of Fisheries and Aquaculture (Ministerio da Pesca e Aqricultura 2010) and based on data from the National Fisheries Satellite Tracking Program (PREPS, https://www.preps.gov.br/). For each industrial fishery, rasterized density maps of vessels (with a hull length greater than 15 m) for 2010 were used and rescaled to values between 0 and 1, using a linear function (Table S1).

Human activity layers—distribution

To assess the general distribution and overlap across the region of the different types of human activities described, rescaled raster layers of each type of human activity were reclassified to create presence/absence (1/0) layers, using the Reclassify tool in ArcMap 10.5.1. Presence/absence layers were then added together to create a map of occurrence of human activities (0–5 activities cell) across the region.

Co-occurrence of turtles with human activities

To quantify the exposure of turtles to each type of human activity, we multiplied the rescaled turtle use layer by each of the rescaled human activity intensity layers, using the Raster Calculator tool in ArcGIS 10.5.1. For turtles during foraging behavior, we considered threats known to occur in high levels in inshore habitats in Brazil where the tracked turtles were observed, namely marine traffic, ports and artisanal fisheries. For turtles during moving behavior, we also considered industrial trawl and gillnet fisheries. The latter were not included in the analysis of the exposure of human activities to foraging turtles, given that the effort of these fisheries is concentrated mostly in offshore waters (Fig. S1). The resulting exposure values were classified based on quartiles (Wildermann 2018) as no exposure (0), low (<0.25), medium (0.25–0.50), high (0.50–0.75) or very high (0.75–1) level of exposure.

We assessed the cumulative exposure of the tracked turtles to threats, which provides a better understanding of the additive effect of overlapping threats (Hart et al. 2018; Maxwell et al. 2013). Cumulative exposure layers for resident and migrant turtles were calculated by adding the individual exposure layers with the Raster Calculator tool, and rescaling (0–1, from no exposure to high cumulative exposure) the resulting layers using the Fuzzy Membership tool with linear membership. The resulting cumulative exposure values were classified based on quartiles (Wildermann 2018) as no exposure (0), low (<0.25), medium (0.25–0.5), high (0.5–0.75) or very high (0.75–1) level of cumulative exposure. We defined "hotspot" areas, as those were high density of turtles and medium to high cumulative threats coexisted.

Results

Distribution of tracked turtles

The mean CCL of tracked turtles was 38.2 ± 3.5 cm and the mean weight was 7.1 ± 1.5 kg. Tracked turtles were caught and released in three blocks (Fig. 2): five

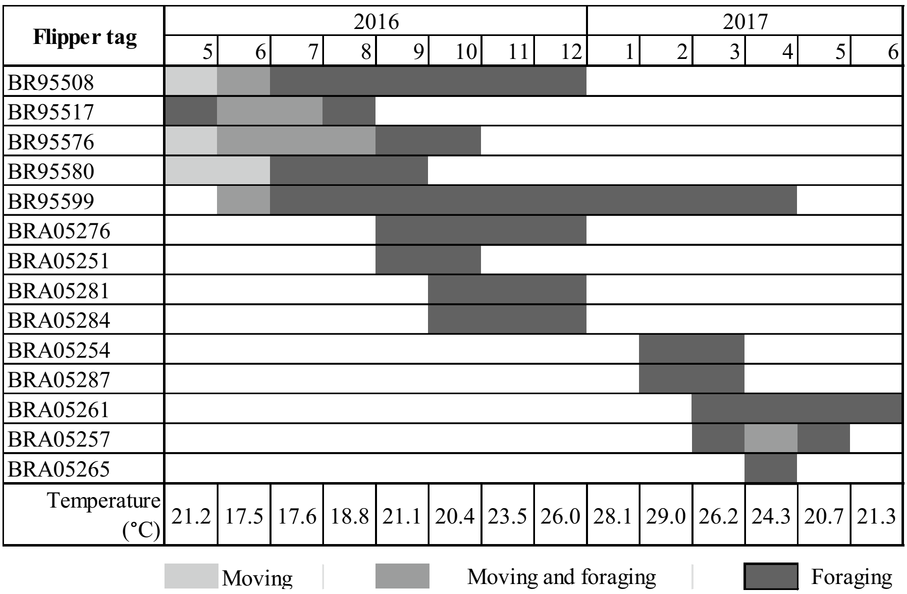

Fig. 2 Temporal distribution of juvenile green turtle tracks by behavioral state (foraging or moving) monthly in 2016 and 2017, and monthly sea surface temperature average. Shade of cells indicate the type of behavior

turtles during the austral early winter months in 2016, four turtles during the late winter months in 2016, and five turtles during mid-late summer months in 2017. Mean tracking duration differed between individuals, with an average of 96 days (± SD 86 days, range 25–345 days). All tracked turtles (n = 14) displayed foraging behavior during their tracking, while only six of them displayed moving behavior (five turtles during early winter months, and BRA05257 in the late summer; Fig. 2). The total area used by turtles during foraging behavior (4872 km^2) was smaller than the total area used during moving behavior (9708 km^2).

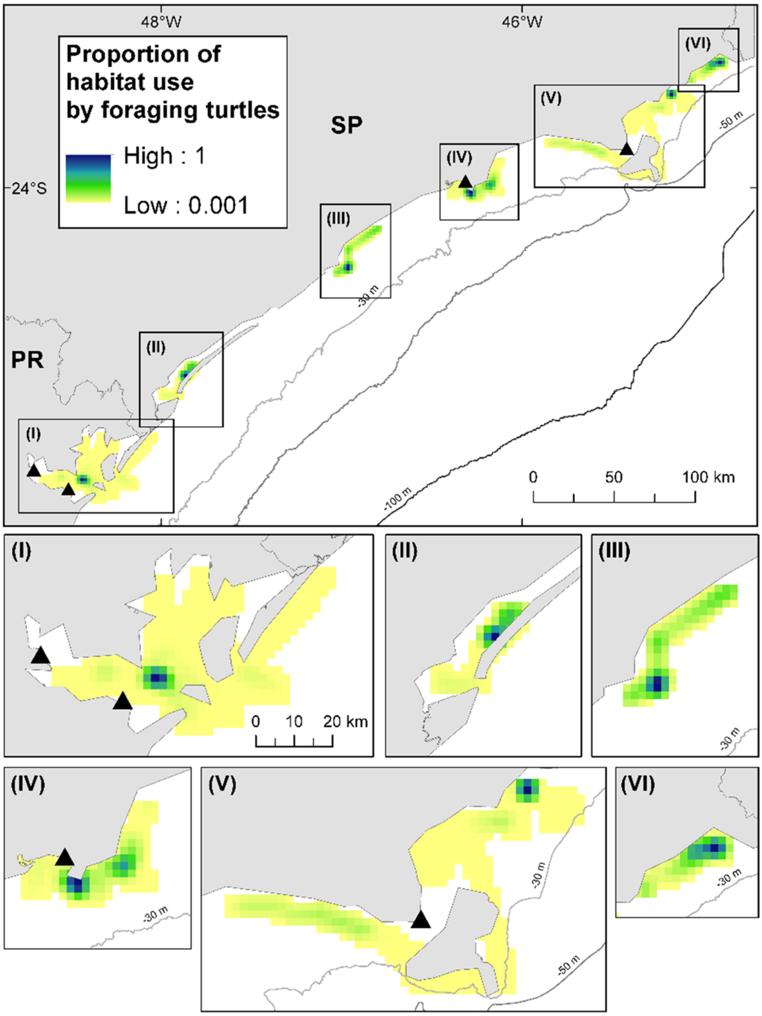

Fig. 3 Space-use by juvenile green turtles (n = 14) within identified foraging grounds: (I) Paranaguá Estuarine Complex (PR), (II) Cananéia bay and Comprida Island (SP), (III) the coast from Peruíbe to Itanhaém (SP), (IV) the Santos Region (SP), (V) the Caraguatatuba region (SP), and (VI) the Ubatuba region (SP); proportion of Space-use by tracked turtles. Turtles were tracked between 2016 and 2017 from Paranaguá Estuarine Complex. Triangles represent ports (from left to right in main figure: Antonina Port, Paranaguá port, Santos port, São Sebastião port). *PR* Paraná state, *SP* São Paulo state

Six distinctive foraging grounds were identified in near-shore coastal areas along southern and southeastern coast of Brazil (Figs. 3, S2), namely: the Paranaguá Estuarine Complex (in PR) (region I); Cananéia-Iguape estuarine lagoon system (in SP) (region II); the coast from Peruíbe to Itanhaém (in SP) (region III); the Santos-São Vicente estuarine system and the adjacent coastal areas in São Paulo state, from Praia Grande to Bertioga (region IV); the Caraguatatuba region (in SP) from Bertioga, around the outer coast of Ilha Bela Island and to Anchieta Island (in SP) (region V); and the Ubatuba region from Itaguá to Praia da Fazenda (in SP) (region VI). The highest density of turtles occurred in the Paranaguá Estuarine Complex (up to seven turtles per cell), followed by the Santos-São Vicente region (in SP) (up to two turtles per cell) (Fig. S2). Within each foraging ground there were distinctive hotspots of space-use (Fig. 3), namely around Cobras Island and Mel Island (in PR) (region I), the south-west coast of Comprida Island (in SP) (region II), south

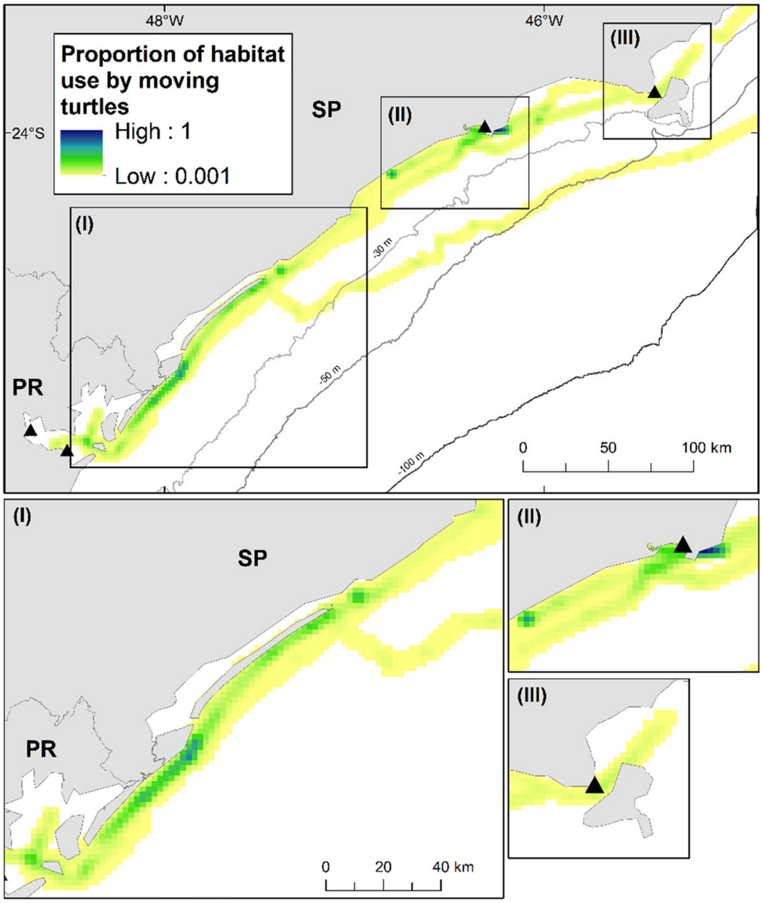

Fig. 4 Space-use by juvenile green turtles (n = 6) along displacement corridors: (I) from Paranaguá Estuarine Complex (PR) to Peruíbe (SP), (II) from Itanhaém to Santos (SP), and (III) channel surrounding Ilha Bela Island (SP). Turtles were tracked between 2016 and 2017 from Paranaguá Estuarine Complex. Triangles represent ports (from left to right in main figure: Antonina port, Paranaguá port, Santos port, São Sebastião port). *PR* Paraná state, *SP* São Paulo state

of Peruíbe (in SP) (region III), between Santos and Guarujá (in SP) (region IV), between Maranduba and Enseada (in SP) (region V), and east of Puruba (in SP) (region VI).

Coastal displacement corridors used by multiple turtles were detected across the study region (Figs. 4, S3). In the southern extent of the region, the corridor spanned across 85 km from Paranaguá Estuarine Complex (in PR) to Peruíbe (in SP), with the higher use areas located 2–6 km from the shore (corridor I; n = 6 turtles). In the central region, a corridor extended for 42 km from Itanhaém to Santos (in SP), with higher use areas located 4–12 km from the shore (corridor II; n = 5 turtles). In the northern region, we identified a smaller corridor spanning 30 km (2.5–16 km from the shore) along the channel between São Sebastião and Ilha Bela Island, including all areas between Bertioga and Ubatuba (in SP) (corridor III; n = 6 turtles). Only turtle BR95576 (34.5 cm CCL) moved into the outer shelf and continued travelling north without reaching a discrete foraging ground throughout the length of the transmission (Figs. 4, S3). A higher proportion of space-use (Fig. 4) during moving behavior was concentrated along the coast between Mel Island (in PR) and Cardoso Island (in SP) (corridor I), along the coast of Itanhaém (in SP) (corridor II-west) and around the Santos-São Vicente region within the bay of Guarujá (in SP) (corridor II-east).

Distribution of human activities

Human activities occurred throughout the extent of the study area (Figs. 5, S1), with the highest concentration of overlapping activities (4–5 activities per cell; Fig. 5) occurring in and near the Paranaguá Estuarine Complex in PR, and in the central-northern São Paulo state, from Itanhaém to Ubatuba. Individual human activities varied in spatial location

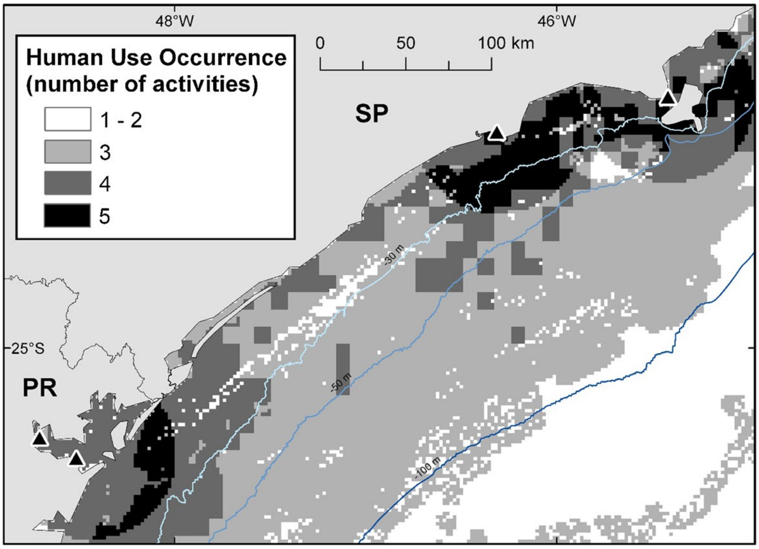

Fig. 5 Map of occurrence of human activities: marine traffic (2014–2015, ports, artisanal fisheries, industrial trawl fisheries, and industrial gillnet fisheries, across the study region. Triangles represent ports (from left to right in main figure: Antonina port, Paranaguá port, Santos port, São Sebastião port). *PR* Paraná state, *SP* São Paulo state

and intensity (Fig. S1). As expected, high and very high levels of marine traffic occurred in inshore waters near ports, as well as at hotspots associated with oil and gas platforms, located at the continental slope (~250 m depth and 230 km from coast) (Fig. S1a). Ports were hotspots of disturbance and the impact within each port region progressively decreased with distance from the ports (Fig. S1b). Artisanal fisheries were of higher intensity in near-shore areas around Paranaguá Estuarine Complex (region I) and the Santos-São Vicente Region (region IV) (Fig. S1c). Trawl fisheries occurred in high and very high intensity in offshore waters (15–50 km from the shore) from the southern extent of Paraná state to Santos-São Vicente Region in São Paulo state, with two distinctive hotspots: one in Paraná state approximately 25 km west of the Paranaguá Estuarine Complex, and one in São Paulo state approximately 20 km off the coast from Itanhaém to Praia Grande, at depths from 15 to 30 m (Fig. S1d). Gillnet fisheries occurred in higher intensity in deeper offshore waters (approximately 100 km from shore, 50 to 100 m depth), and in a smaller area near Paranaguá Estuarine Complex (region I) (Fig. S1e).

Exposure of foraging turtles to human activities

A very high proportion (88.1%, 4292 km^2) of the total foraging area utilized by tracked turtles (4872 km^2) was exposed to the cumulative impact of human activities (marine

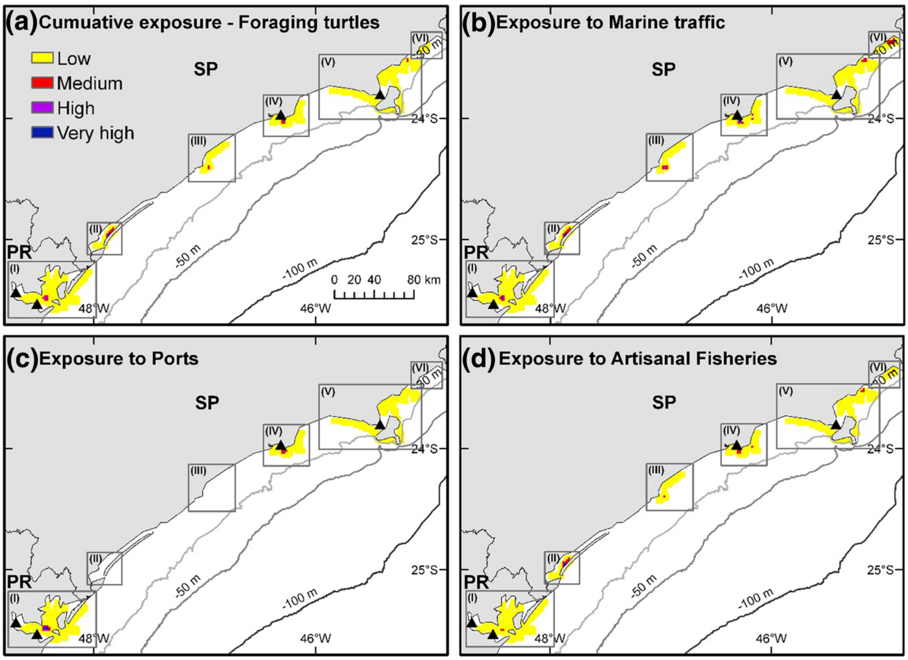

Fig. 6 Exposure of foraging turtles tracked between 2016 and 2017 from Paranaguá Estuarine Complex to human use activities: **a** cumulative exposure (zoom-ins in Fig. S4), **b** marine traffic (zoom-ins in Fig. S5), **c** ports (zoom-ins in Fig. S6) and **d** artisanal fisheries (zoom-ins in Fig. S7). Extents indicate foraging grounds of the tracked turtles: (I) Paranaguá Estuarine Complex (PR), (II) Cananéia bay and Comprida Island (SP), (III) the coast from Peruíbe to Itanhaém (SP), (IV) the Santos Region (SP), (V) the Caraguatatuba region (SP), and (VI) the Ubatuba region (SP). *PR* Paraná state, *SP* São Paulo state. Triangles represent ports (from left to right in main figure: Antonina port, Paranaguá port, Santos port, São Sebastião port)

Table 2 Total area in km^2 (%) used by tracked turtles exposed to different levels of cumulative human activities in the southern and southeastern coast of Brazil

Level of exposure	Marine traffic	Ports	Artisanal fisheries	Trawlers	Gillnets	Cumulative
	Proportion of area in km^2 (%)					
Foraging turtles (n = 14)						
No exposure	480 (9.9)	1376 (28.2)	604 (12.4)	N/A	N/A	580 (11.9)
Low (< 0.25)	4204 (86.3)	3432 (70.4)	4176 (85.7)	N/A	N/A	4192 (86.0)
Medium (0.25–0.50	140 (2.9)	36 (0.7)	80 (1.6)	N/A	N/A	76 (1.6)
High (0.50–0.75)	36 (0.7)	20 (0.4)	8 (0.2)	N/A	N/A	20 (0.4)
Very high (0.75–1)	12 (0.2)	8 (0.2)	4 (0.1)	N/A	N/A	4 (0.1)
Moving turtles (n = 7)						
No exposure	644 (6.6)	5548 (57.1)	2964 (30.5)	308 (3.2)	3108 (32.0)	452 (4.7)
Low (< 0.25)	8932 (92.0)	4100 (42.2)	6700 (69.0)	9388 (96.7)	6600 (68.0)	9256 (95.3)
Medium (0.25–0.50	116 (1.2)	52 (0.5)	44 (0.5)	12 (0.1)	0 (0.0)	0 (0.0)
High (0.50–0.75)	8 (0.1)	8 (0.1)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Very high (0.75–1)	8 (0.1)	0 (0.0)	0 (0)	0 (0.0)	0 (0.0)	0 (0.0)

traffic, ports and artisanal fisheries), with 86% (~4200 km^2) exposed to low levels of cumulative exposure to human activities (Figs. 6a, S4; Table 2). The remaining 11.9% of area used by foraging turtles (580 km^2) was not exposed to the cumulative impact of any of the considered human activities (Table 2). Medium to very high levels of cumulative exposure were detected in the channels near Cobras Island in the Paranaguá Estuarine Complex (region I), in the southwestern coast of Comprida Island (in SP) (region II), south of Peruíbe (in SP) (region III), south of Santos (region IV), and within the Fortaleza bay in the Caraguatatuba region (in SP) (region V) (Figs. 6a, S4; Table 2).

In terms of exposure of foraging turtles to individual human activities (Figs. 6b–d, S5–S7), medium to very high levels of exposure varied among regions. In the Paranaguá Estuarine Complex (region I) turtles were exposed to all human activities, with medium levels of exposure to artisanal fisheries (Figs. 6d, S7-I), and medium to very high exposure to marine traffic (Figs. 6b, S5-I) and ports (Figs. 6c, S6-I). Within the Cananéia-Iguape estuarine/lagoon system and along the coastal area of Comprida Island (in SP) (region II), we detected medium to very high levels of exposure to marine traffic (Figs. 6b, S5-II) and artisanal fisheries (Figs. 6d, S7-II), but no exposure to port activities (Figs. 6c, S6-II). Along the coast from Peruíbe to Itanhaém (in SP) (region III), turtles were less exposed to the human activities considered here, with medium to high levels of marine traffic (Figs. 6b, S5-III), no exposure to ports (Figs. 6c, S6-III), and restricted areas exposed to medium levels of artisanal fisheries (Figs. 6d, S7-III). The Santos-São Vicente region (region IV) displayed some areas of medium to very high exposure to marine traffic (Figs. 6b, S5-IV), medium to high exposure to ports

(Figs. 6c, S6-IV), and medium exposure to artisanal fisheries (Figs. 6d, S7-IV). Within the Caraguatatuba region (region V) turtles near Fortaleza Bay were exposed to medium to high levels of marine traffic (Figs. 6b, S5-V), low exposure to ports (Figs. 6c, S6-V), and medium levels of artisanal fisheries (Figs. 6d, S7-V). Lastly, turtles foraging in the Ubatuba (region VI) were highly exposed to marine traffic (Figs. 6b, S5-VI), mostly low to medium exposure to artisanal fisheries (Figs. 6d, S7-VI), and no exposure to ports (Figs. 6c, S6-VI).

Exposure of moving turtles to human activities

A substantial proportion of the area used by turtles during moving behavior (95.3%, 9256 km^2) was exposed to low cumulative impact of human activities (marine traffic, ports, artisanal, trawl and gillnet fisheries), with no areas of medium to very high levels of cumulative exposure (Figs. 7a, S8; Table 2). The remaining 4.7% of area used by moving turtles (452 km^2) was not exposed to the cumulative impact of the human activities considered here (Table 2).

Moving turtles were mainly exposed to marine traffic (93.4%, 9064 km^2; Figs. 7b, S9) and trawlers (96.8%, 9400 km^2; Figs. 7e, S12), followed by artisanal (69.5%, 6744 km^2; Figs. 7d, S11) and gillnet (68%, 6600 km^2; Figs. 7f, S13) fisheries, and a lower proportion of area exposed to ports (42.9%, 4160 km^2; Figs. 7c, S10) (Table 2). Low levels of exposure to each human activity were detected in all displacement corridors (Figs. 7b–f, S9–13). Medium to very high levels of exposure of moving turtles to all individual human activities were detected (Figs. 7b–e, S9–12), with the exception of gillnet fisheries (Figs. 7f, S13). Along the southern turtle displacement corridor (corridor I; n = 6 turtles) we detected medium levels of marine traffic (Figs. 7b, S9-I) and ports (Fig. 7c, S10-I) in the channels between Cobras Island and Mel Island in the Paranaguá Estuarine Complex, medium exposure to marine traffic (Figs. 7b, S9-I) and artisanal fisheries (Figs. 7d, S11-I) in the vicinities of Cardoso Island (in SP) and medium exposure to marine traffic (Figs. 7b, S9-I) north of Comprida Island (in SP). Turtles moving along the central corridor (corridor II; n = 5 turtles) in the Santos-São Vicente region were exposed to higher levels of marine traffic (Figs. 7b, S9-II) and ports (Figs. 7c, S10-II), and medium levels of artisanal fisheries (Figs. 7d, S11-II) and trawl fisheries (Figs. 7e, S12-II). Lastly, within the most northern corridor (corridor III; n = 3 turtles), there were no areas exposed to medium to very high levels of the human activities considered in this study (Fig. 7b–f, and inset III in Fig. S9–13).

Discussion

Juvenile green turtles using the coast of Paraná and São Paulo states in Brazil are exposed to an array of human activities, with most of the region exposed to low levels of cumulative threat exposure, but five areas identified as "hotspot" threat areas (Cobras Island (in PR), Comprida Island (in SP), south of Peruíbe (in SP), Santos-São Vicente (in SP), and Caraguatatuba region (in SP)). Low exposure areas with high turtle use are good candidates for long-term protection projects, while medium/high exposure areas potentially require prompt local management intervention and monitoring of impacts. All of these areas are already surrounded or included in Protected Areas (e.g., APA de Guaraqueçaba, Ecological Station of Mel Island, APA Cananéia-Iguape-Peruíbe, APA Marinha Litoral Sul and Litoral

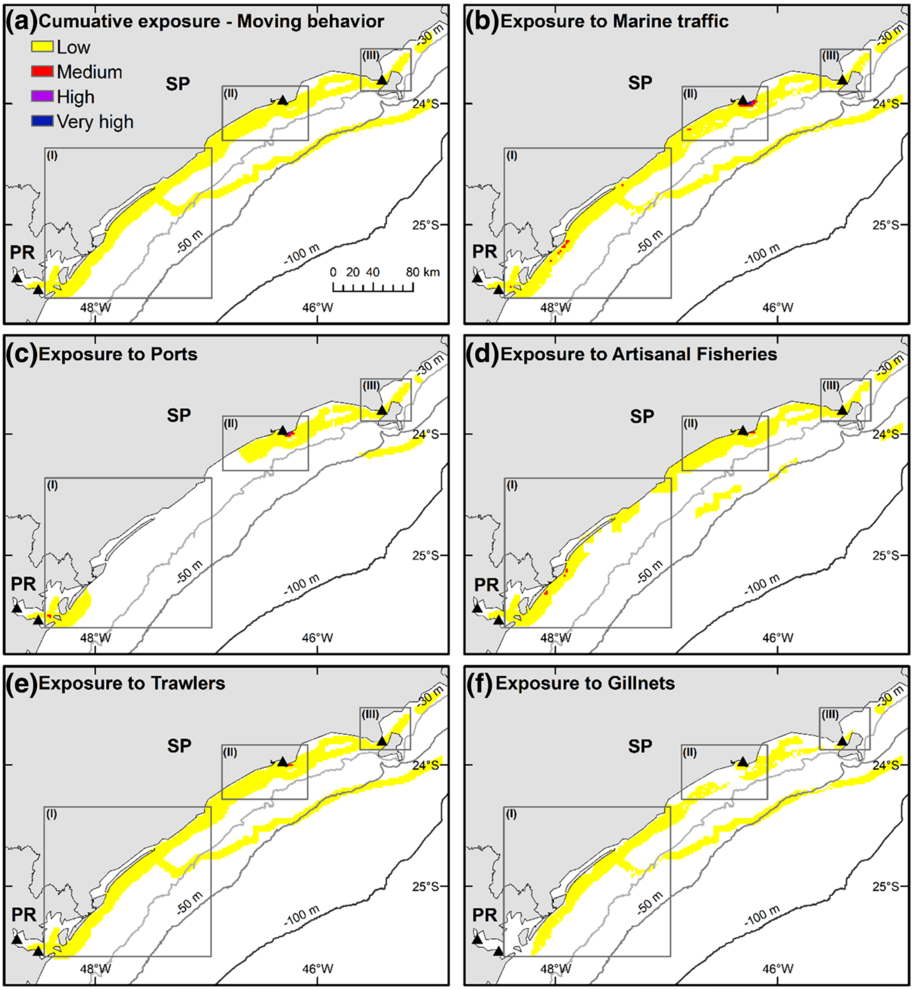

Fig. 7 Exposure of moving turtles tracked between 2016 and 2017 from Paranaguá Estuarine Complex to human use activities: **a** cumulative exposure (zoom-ins in Fig. S8), **b** marine traffic (zoom-ins in Fig. S9), **c** ports (zoom-ins in Fig. S10), **d** artisanal fisheries (zoom-ins in Fig. S11), **e** industrial trawl fisheries (zoom-ins in Fig. S12), and **f** industrial gillnet fisheries (zoom-ins in Fig. S13). Extents indicate displacement corridors used by the tracked turtles: (I) from Paranaguá Estuarine Complex (PR) to Peruíbe (SP), (II) from Itanhaém to Santos (SP), and (III) channel surrounding Ilha Bela Island (SP). PR: Paraná state; SP: São Paulo state. Triangles represent ports (from left to right in main figure: Antonina port, Paranaguá port, Santos port, São Sebastião port)

Norte of São Paulo state) (Magris et al. 2013), however they are protected under multiple-use area restrictions (IUCN category VI; Dudley 2008), which means that extractive activities, like fishing, are allowed. Therefore, to further minimize exposure of marine turtles in the region to human activities and potential associated impacts, more restrictive management zones (e.g., no-take zones) could be proposed and implemented within the already established Protected Areas, particularly in areas that were identified as hotspots and corridors for marine turtles. However, the political and logistical feasibility of implementation needs to be determined (Fuentes et al. 2015). To achieve this, it is necessary to consider the impact of each activity in the region, the potential economic and socio-cultural impacts of managing them, and the spatial–temporal use of the region by turtles (Gredzens et al. 2014; Oliveira Leis et al. 2019). As evidenced in our study, marine turtles using the southern and southeastern coast of Brazil have seasonal patterns moving large distances in the cooler months in search of resources and/or optimal environmental conditions (Carman et al. 2012; Godley et al. 2003; Shaver et al. 2013; Torezani et al. 2009; Vélez-Rubio et al. 2018). Here, we assumed constant effort throughout the year for each of the human activties, which might not be the case, as for example, fishing practices vary seasonally to align with resources and weather (López-Barrera et al. 2012). Thus, coupled information on the seasonal variation of human aactivities with turtle space-use at "hotspot" threat areas could be used to identify alternatives for restrictive management strategies, which might include dynamic Marine Protected Areas or seasonal closures and restriction of specific activities and gear use (Maxwell et al. 2015). These strategies, although more challenging to implement and to enforce, may increase compliance, especially when engaging stakeholders throughout the process, as they are less restrictive than no-take zones (Carr and Heyman 2016; Maxwell et al. 2015).

Artisanal fishery was identified as one of the human activities, considered here, to which juvenile green turtles were most exposed to at the southern and southeastern coast of Brazil. Artisanal fisheries are a recognized issue for marine turtles, as by-catch, particularly for juvenile green turtles along the southern and southeastern coast of Brazil (Santos et al. 2011), as this species uses mostly shallow coastal waters which overlaps with fishing activities along the coast of Paraná and São Paulo states (Bahia and Bondioli 2010; Isaac et al. 2006). Efforts to mitigate the impacts of fisheries on marine turtles, particularly in the state of São Paulo, have been undertaken by several institutions and groups (Awabdi et al. 2018; Gallo et al. 2006; López-Barrera et al. 2012; Marcovaldi et al. 2006; Nagaoka et al. 2008; Silva et al. 2017). However, the need for long-term efforts, focusing on capacity building, enforcement and the modification of fishing practices and gear (e.g., soak time, net length or changes in spatial or seasonal use of gear) has been highlighted (Gallo et al. 2006; López-Barrera et al. 2012; Monteiro et al. 2016).

Both resident and transient foraging juvenile green turtles were also highly exposed to marine traffic, which was associated with areas with fishing activities, ports, and oil and gas platforms. Regardless of the overlap between areas used by turtles and marine traffic, evidence of the actual impact from exposure to marine traffic is limited for the region, with opportunistic information obtained from stranding events from other locations in Brazil (e.g., see Monteiro et al. (2016) for Rio Grande do Sul state). Similarly, ports and associated activities (e.g., dredging, port-related vessel traffic, introduction of non-native species, and leaching of toxic antifoulants) can impact marine turtles and biodiversity at multiple temporal and spatial scales (Grech et al. 2013), but limited information has been published on the actual impact of ports, and associated activities, on marine turtles in the region or elsewhere (however see Goldberg et al. 2015).

Despite the lack of quantifiable information on the impacts of these activities on marine turtles in the region, existing programs that monitor for marine megafauna stranding along the São Paulo, Paraná and Santa Catarina coasts have reported the impact of multiple anthropogenic threats to juvenile green turtles in the region. Nevertheless, the lack of quantified information on the spatial–temporal intensity and magnitude of the impact of anthropogenic activities on marine turtles and their habitat hinders appropriate management and conservation initiatives. In addition to understanding the actual impact of these activities, there is the need to understand their relative impact to each other and their cumulative and synergetic impacts to inform and guide prioritization and allocation of resources (Fuentes et al. 2015; Klein et al. 2016).

Quantifying specific impacts at a broad spatial scale can be logistically difficult (Dawson et al. 2017). Although, our spatially explicit assessments to identify "hotspot" threat areas did not account for the actual impacts of each threat, it allowed us to compare exposure to threats at a large spatial extent in a consistent way, which can now inform on-the ground efforts where further impact assessments and management interventions are needed and can be undertaken (Myers et al. 2000). Such an approach is particularly useful for broad scale prioritization of conservation actions and is a necessary precursor to site-level management (Fuentes et al. 2016). Future efforts can now focus on the "hotspot" threat areas identified here to quantify specific impacts and identify site-specific management strategies.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due to containing sensible information on the location of endangered species but are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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