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Using drones and ROV to assess the vulnerability of marine megafauna to the Fundão tailings dam collapse

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HIGHLIGHTS

- With Drone-monitoring it was possible to assess the density of cetaceans that use the Rio Doce mouth.
- Marine megafauna uses the area closest to the mouth of the estuaries in the summer.
- Highest density of marine megafauna occurred in areas where the seafloor was muddy.
- Marine megafauna species using the area impacted, in the Rio Doce, for foraging.

GRAPHICAL ABSTRACT

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ABSTRACT

The ecology and life history of marine megafauna can answer the ecological importance of a region. This study assesses and monitors the abundance and home range of sea turtles, seabirds, marine mammals and the association with coastal microhabitats in potentially impacted areas at the Rio Doce river mouth, Comboios, and Piraquê-açu river mouth after the collapse of the Fundão dam. Remotely Operated Vehicles (ROV) and UAVs (Unmanned Aerial Vehicles, or drones) were used for megafauna species identification, behavior, population data, habitat characterization, and monitoring of environmental protection areas. The species *Sotalia guianensis* and *Pontoporia blainvillei* were the most recorded cetaceans, and the main observed behavior was feeding. Guiana dolphin (*S. guianensis*) occurs in greater density in the Rio Doce river mouth region, resulting in more than 10 sightings/km^2, while franciscana (*P. blainvillei*) were the most concentrated Comboios area. The seabirds (all species) had up to 15 sightings/km^2 at the Rio Doce river mouth, the highest density among sampled areas. The green turtle (*Chelonia mydas*) was the most frequently recorded, followed by the leatherback turtle (*Dermochelys coriacea*). The green turtle occurred at a higher concentration at the Piraquê-Açu river mouth (above 6 sightings/km^2). The sites closest to Rio Doce river mouth and Comboios predominantly showed mud bottoms, while those at Piraquê-Açu mouth were mostly reef structures. The estuarine areas showed greater importance for megafauna than marine areas.

1. Introduction

Marine megafauna can provide an evaluation of the ecological importance of a region and is therefore often used as a tool for the creation

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of environmental protection areas (Hooker and Gerber, 2004). Cetaceans' ecology and life histories, such as high life expectancy, wide distribution or habitation in coastal regions, and high trophic level, make them sentinels of the marine environment (Bossart, 2011; Hooker and Gerber, 2004; Moura, 2009). Sea turtles and seabirds are also key species for conservation in many parts of the world (Chatwin, 2007; Campbell, 2007), mainly due to their large migrations between feeding and breeding areas (Schofield et al., 2010; Yorio, 2009).

The coastal region near the Rio Doce river mouth is home to critically endangered populations of the leatherback turtle (*Dermochelys coriacea*) and the franciscana (*Pontoporia blainvillei*) (Barreto et al., 2021); therefore, it is considered a high-priority area for the conservation of the Brazilian marine biodiversity (Magris et al., 2019). Anthropic impacts such as incidental fishing and pollution of aquatic environments are significant threats to these animals (Kühn and van Franeker, 2020; Oliveira, 2018). Due to the difficulty in accessing these animals, technological innovations and tools can optimize studies to conserve threatened species and promote advances in scientific understanding (Wilmers et al., 2015). Cameras, for example, allow us to remotely monitor marine animals (Torres et al., 2018), assess habitat use and behavior (Raoult et al., 2018), as well as accessing ecological parameters (Schofield et al., 2019).

Drones or Unmanned Aerial Vehicles (UAVs) have been used for species identification, behavioral studies, population data collection, habitat characterization, and environmental protection area monitoring (Brooke et al., 2015; Drever et al., 2015; Smolowitz et al., 2015; Casella et al., 2016), including with marine megafauna (Bevan et al., 2018; Schofield et al., 2017). The use of Remotely Operated Underwater Vehicles (ROV) has also proven to be an alternative for estimating the abundance of aquatic species (Karpov et al., 2012) and is a robust tool for identifying pressures on marine ecosystems (Sward et al., 2019).

The 2015 Mariana disaster dumped thousands of tons of metal ore tailings containing many potential contaminants in the coastal region adjacent to the Rio Doce river mouth (Magris et al., 2019). These regions are known for the marine megafauna aggregating effect associated with their use for food, development, and reproduction caused by input and retention of mineral nutrients and organic matter, which structure energy-rich food chains (Bakun, 1996; Mann and Lazier, 2006). Hence, the aggregating effect in impacted areas can enhance the vulnerability of populations already highly threatened, resulting in the urgency for efficient long-term monitoring due to the high life expectancy of these species.

The present study assesses the abundance, home range, and habitat use of sea turtles, seabirds, and marine mammals near the Rio Doce river mouth, southeastern Brazil, the most affected coastal area of ore tailings from the Mariana disaster. We also evaluate the associations between megafauna and several coastal microhabitats, including trends in aggregation and displacement in a coastal area impacted by a significant environmental disaster.

2. Material and methods

2.1. Study area

The study occurred on the northern coast of the state of Espírito Santo, Brazil, between the Piraquê-Açu river mouth (-20°0'00"S -40°0'00"W) and the northern limit of the Espírito Santo coast (-18°30'00"S -39°30'00"W). Drone-monitoring was concentrated at the Rio Doce river mouth, with two take-off points located at Regência beach and Comboios Biological Reserve (county of Linhares). An additional take-off point at Coqueiral beach, at Piraquê-Açu river mouth (county of Aracruz) was considered a control (Table 1; Fig. 1). Furthermore, other studies as manned overflights, bioacoustics, and onboard monitoring for megafauna observation (RRDM, 2019) were realized from the southern limit of Santa Cruz Wildlife Refuge and Environmental Protection Area (APA) Costa das Algas to the northern limit of Espírito Santo, and obtained representative points for aggregation areas of marine megafauna. We used these aggregation points for exploring the region by underwater mapping carried out with the aid of an ROV (Fig. 2) to understand the environments most occupied by marine megafauna in the region impacted by the dam's rupture.

Table 1
Sampling stations of the marine megafauna drone-monitoring.

Sample station	UTM_Y	UTM_X	Takeoff point	Sampled area
Doce	7826436,443	414092,5491	Regência beach	8 km^2
Comboios	7823240,301	405046,1961	Comboios biological reserve	8 km^2
Piraquê	7794646,911	381053,9376	Coqueiral beach	4 km^2

2.2. Data collection and analysis

2.2.1. Drone-monitoring

The drone used was the DJI Mavic 2 Zoom model and a Virtual Reality Mask - First Person View (FPV) to observe the fauna during the flight. This quadcopter Vertical Take-Off and Landing (VTOL) was considered the most appropriate UAV for this study due to the camera's resolution capacity record in 4 k 30fps, with the possibility of zooming up to 4 times. For each drone operation, authorization was obtained from the Department of Airspace Control (DECEA/AIC - N 21/10). The systematized collections occurred between January 2019 and March 2020, totalizing 15 campaigns (divided into 5 quarters), with the following team: Remote Pilot, Copilot, Drone Observer, Fauna Observer, Logistic Operator.

The start of the transect is a fixed point. In Linhares, points locations are close to the Rio Doce river mouth, and the sea is under the influence of the river plume. Therefore, two transects are made from each take-off point, while in Aracruz, only one transect was done. Flights were designed to obtain the largest swept area with a minor overlap (Barreto et al., 2021). At drone height 50 m to the sea surface and camera tilt angle of -27°, the drone flies in lateral position at a speed of 40 km/h, each transect covering 8.2 km, sweeping an area of 4km^2 (Barreto et al., 2021).

Each area is sampled with six (6) full replicates within each campaign, totalizing 30 flights per campaign. Field effort was interrupted when the Beaufort scale reached 4 or surface wind got above 26 km/h. Each transect performed represents a sample, which was analyzed in the laboratory by a researcher and validated by another. Also, the start and end time and geographic position of the sighting are recorded.

Cetacean species and numbers in each transect were determined, distinguishing adults, juveniles, and calves. A group of cetaceans consists of one or more individuals. Behavior (Swimming, Feeding, and Interaction) was also recorded whenever possible. The determination of the behaviors recorded with drone-monitoring was based on previous studies conducted along the Brazilian coast (Rossi-Santos and Flores, 2009; Azevedo et al., 2007; Flores and Fontoura, 2006; Daura-Jorge et al., 2005). For sea turtles, age groups could have been estimated if individuals had been recorded longer during drone monitoring. Unfortunately, for seabirds, most records were only down to the family level due to the difficulty of identifying the species during flight. Similarly, it was only possible to characterize their behavior and age class when the observation time was longer.

Results were interpreted to determine the density of sightings (records/km^2); density of individuals (individuals/km^2); behavior (as a percentage of records); and percentage of each age class; by quarters (five seasons: summer, autumn, winter, spring, and summer again) and location (three locations). The results were presented in monthly and overall representations, considering the entire period sampled for the density of sightings and percentage of age class. In addition, the density of individuals was analyzed and compared among the five quarters,

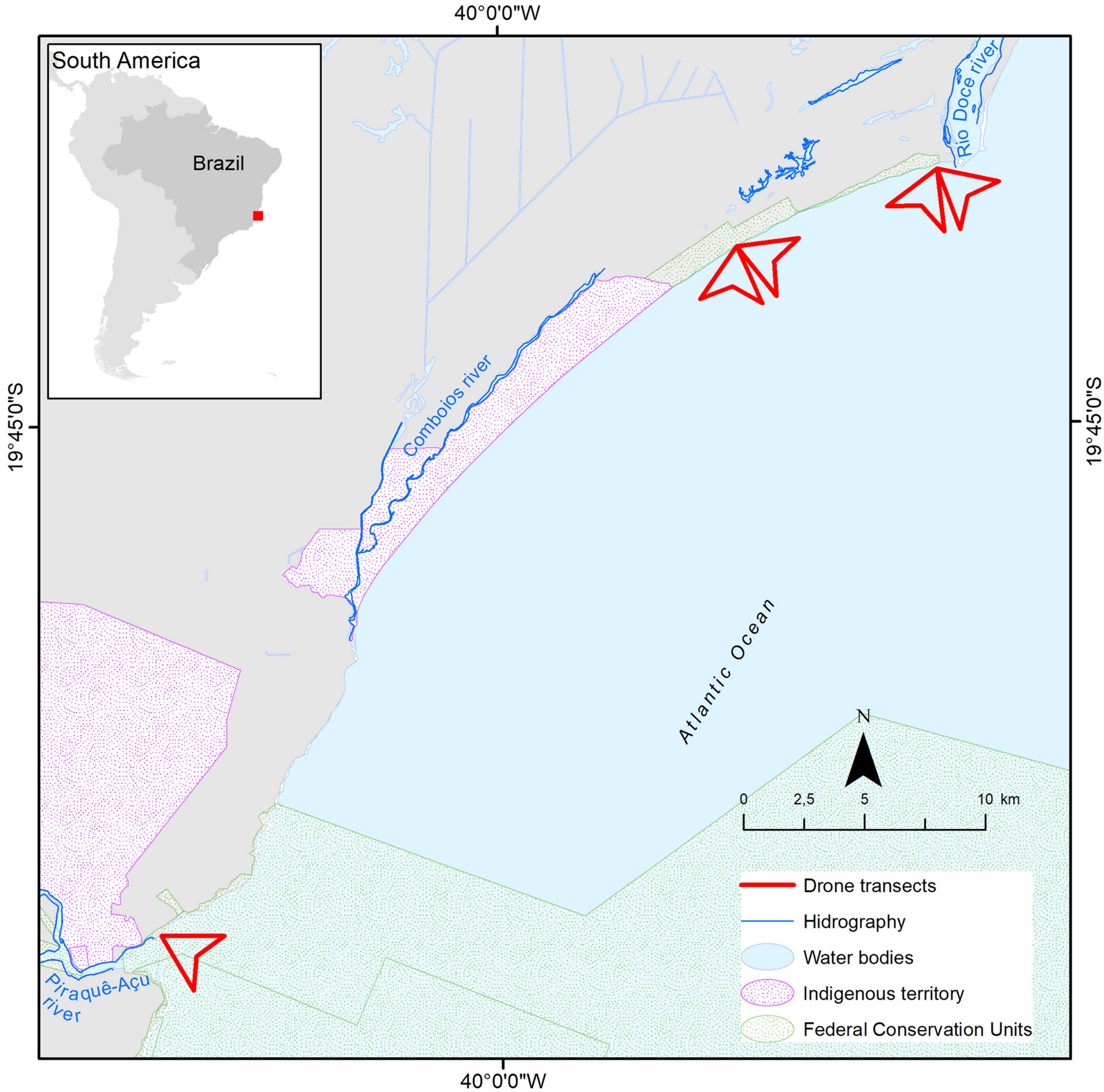

Fig. 1. Sampling design of the marine megafauna drone-monitoring near Rio Doce river, southwest brazilian coast.

and the percentage of feeding behavior was analyzed seasonally. All analyses were performed in the statistical package R Project (R Development Core Team, 2008), and results were presented in boxplots, percentage plots, or point means with associated standard error. The Mann-Whitney statistical test was nonparametric for two independent samples at 0.05 level of significance (Zar, 1984).

2.2.2. ROV - habitat mapping

In order to determine the influence of the main micro-habitats related to the megafauna observed by the drone-monitoring, the Blue Robotics BlueROV2 model with 300 m of umbilical cable available was used for the underwater sampling and data collected in Full HD. In this operation, a 100 m long transect was performed, navigating linearly. The distance was calculated from the moment the equipment touches the bottom, using measurement markings on the ROV's umbilical cable. Effort control is made more effective with an underwater GPS attached to the ROV, allowing complete administration of the distance traveled. In addition, the ROV sensors collect other transect information such as depth, visibility, and current.

The equipment is piloted with a remote control connected to a computer, where the ROV operator visualizes what is ahead. The operator points out events to the note taker along the transect, using recording time to locate changes in environment, fauna, and flora. Each dive was a sample, which required further analysis in the laboratory. Identifying the types of habitats is made from the predominant substrate or the predominant organisms, necessary to identify and describe the bottom types with records of feeding behavior or aggregation of megafauna. The substrates are classified into seven morphotypes: sand; sand and mud; sand with calcareous shell fragments; reef structures; bryozoans/sponges and algae; mud; and rhodoliths. In addition, the taxonomic structure of fish and benthos was recorded. With information previously obtained with geophysical instruments, habitat classes were extrapolated, respecting the limits of the known bottom types data obtained from the literature (Bastos et al., 2015; de Oliveira et al.,

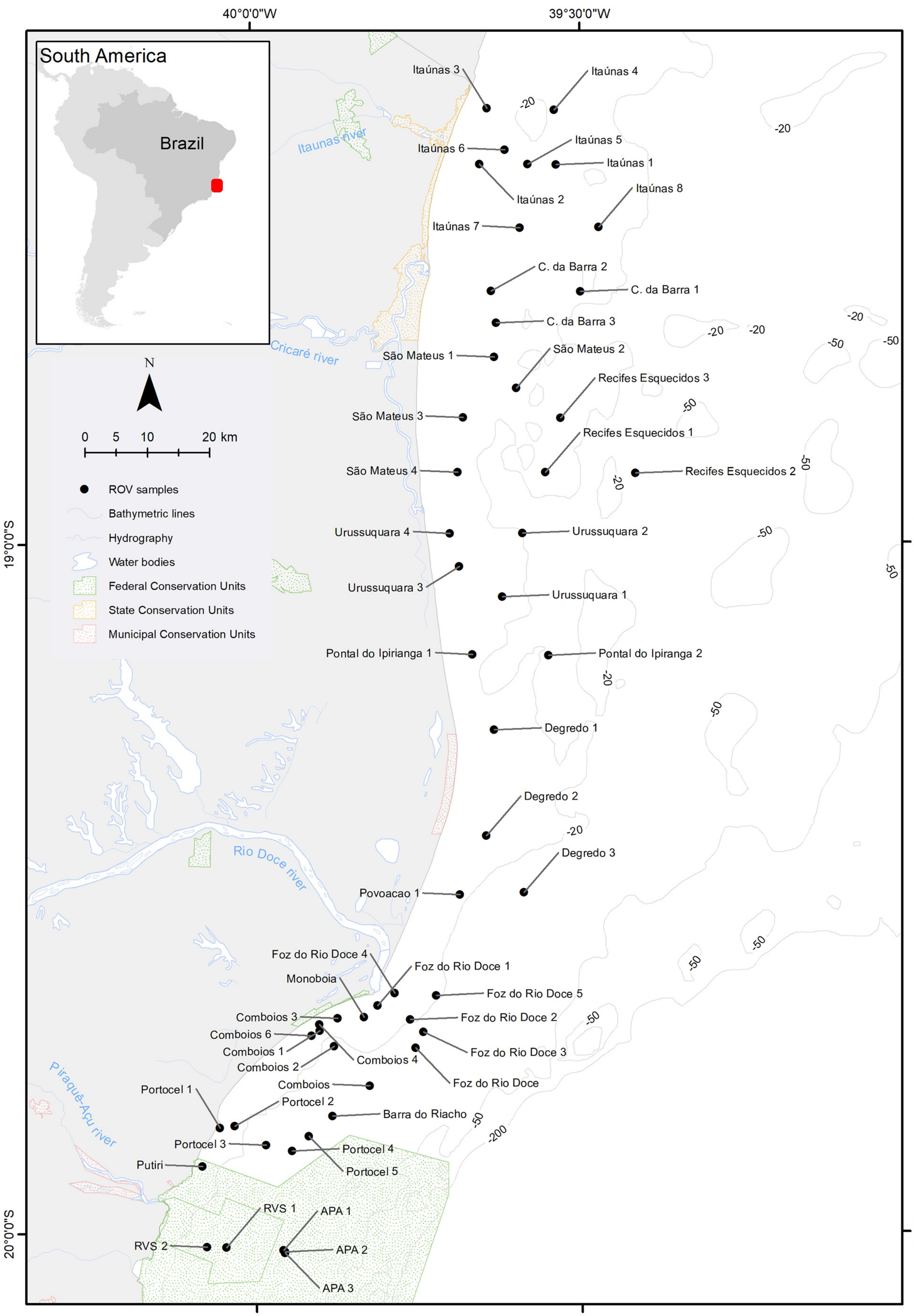

Fig. 2. Sampling performed to identify seafloor type with ROV near Rio Doce river, southwest brazilian coast.

2020). In this way, we estimated the spatial correlation between habitat classes and the occurrence and behavior of marine megafauna.

3. Results

3.1. Drone-monitoring

The taxonomic classification of the marine megafauna recorded through drone-monitoring is described in Table 2. Also, the number of sightings and the global threat classification, according to the International Union for Conservation of Nature (IUCN); national, according to the Ministry of Environment (MMA); and state (IEMA).

3.1.1. Density in study areas

3.1.1.1. Cetaceans. *S. guianensis* was recorded in all areas, resulting in more than 10 sightings/km^2 at the point closest to the Rio Doce river mouth. The density of records was lower in Comboios (up to 5 sightings/km^2) and Piraque-Açu river mouth (up to 3 sightings/km^2) (Fig. 3). *Pontoporia blainvillei* (franciscana) was recorded only in Comboios and Rio Doce river mouth (Regência), while in the region of Piraquê-Açu, there was no record of the species. The highest concentration of individuals was found in the area of Comboios (up to more than 4 sightings/km^2) (Fig. 3), where fransicana were sighted in all five seasons sampled (Fig. 4).

3.1.1.2. Sea Turtles. The green turtle was the species most frequently observed in all monitored areas, although there were also isolated records of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) (Table 2). The green turtle occurred in higher concentration at the Piraquê-Açu river mouth (above 6 sightings/km^2). In other areas, concentration did not exceed 3 records per km^2 (Fig. 3).

3.1.1.3. Seabirds. All records of seabirds were combined to assess density. Up to 15 sightings/km^2 were recorded at the Rio Doce river mouth. The density of records was lower at Comboios (up to 5 sightings/km^2), and the Piraquê-Açu river mouth presented no records (0.01 sightings/km2) (Fig. 3).

3.1.2. Density by quarters and behavior

3.1.2.1. Cetaceans. A total of 262 groups of cetaceans were observed. *Sotalia guianensis* (Guiana dolphin; 184 groups) and *Pontoporia blainvillei* (franciscana; 42 groups) were the species with the most records (Table 2). The density of *S. guianensis* was significantly lower in some specific quarters, mainly during meridional spring and fall (4 and 3 quarters). Feeding behavior was observed in more than 50% of the records in all sampled periods. Foraging was present throughout the study in all areas being the most common behavior recorded, followed by commuting and interaction (Fig. 4). At the Rio Doce river mouth, the *P. blainvillei* density of records was lower (< 1 sighting/km^2), and no individuals of this species were recorded in the 2nd, 3rd, and 4th seasons/quarters (autumn, winter, and spring) of 2019. The area monitored in Comboios was consolidated as the main habitat used by *P. blainvillei* in the region, highlighting their feeding behavior, consistently observed in drone records. At the Rio Doce river mouth, swimming and interaction between individuals were observed (Fig. 4).

3.1.2.2. Sea Turtles. Among the 221 sightings made during the study, 184 were identified as green turtles (*Chelonia mydas*), and five were leatherback (*Dermochelys coriacea*). The Piraquê-Açu river mouth represents a vital feeding ground for *C. mydas*. Foraging was above 60% in most trimesters, except for the 4th trimester of 2019 (40%) (Fig. 4).

3.1.2.3. Seabirds. During the 15 months of the study, 3786 seabirds and shorebirds were recorded. Identification at a specific level was impossible for most records. However, eight taxa were identified: *Fregata magnificens*, *Phaetusa simplex*, *Mycteria americana*, *Sula leucogaster*, *Sterna hirundo*, *Thalassarche* sp., *Egretta thula* and, *Sula dactylatra* (Table 2). Therefore, the data indicate greater habitat use by birds at

Table 2
Registered taxons list in the monitoring of marine megafauna near Rio Doce river, southwest brazilian coast. NT (Near Threatened), VU (Vulnerable), DD (Data Deficient), EN (Endangered), CR (Critically Endangered), LC (Least Concern), NE (Not Evaluated).

Taxa	Common name	Population trend			Number of records			
		IUCN	MMA	ES	Doce	Comboios	Piraquê	Total
Cetaceans								
Sotalia guianensis	Guiana Dolphin	NT	VU	DD	452	123	80	655
Steno bredanensis	Rough-toothed Dolphin	LC	NE	DD		10		10
Pontoporia blainvillei	Franciscana	VU	CR	EN	16	125		141
No ID	Dolphin	–	–	–	51	18		69
Sea Turtles								
Chelonia mydas	Green Turtle	EN	VU	VU	10	15	159	184
Caretta caretta	Loggerhead Turtle	VU	EN	VU		1		1
Lepidochelys olivacea	Olive Ridley	VU	EN	EN		2		2
Dermochelys coriacea	Leatherback	VU	CR	CR		5		5
No ID	Sea Turtle	–	–	–	9	7	13	29
Seabirds								
Phaetusa simplex	Large-billed Tern	LC	NE	NE	160	2		162
Sterna hirundo	Common Tern	LC	NE	NE		30		30
No ID	Tern	–	–	–	1367	290	182	1839
Mycteria americana	Wood Stork	LC	NE	NE	1			1
Egretta thula	Snowy Egret	LC	NE	NE	1			1
Thalassarche sp.	Albatross	–	–	–			1	1
Fregata magnificens	Magnificent Frigatebird	LC	NE	NE	1	1	1	3
Sula dactylatra	Masked Booby	LC	NE	NE		1	1	2
Sula leucogaster	Brown Booby	LC	NE	NE	20	58	17	95
No ID	Seabird	–	–	–	967	283	402	1652
Rays and Sharks								
Rhincodon typus	Whale Shark	EN	VU	VU	1			1
Aetobatus narinari	Spotted Eagle Ray	QA	NA	NA			1	1
No ID (Chondrichthyes)	Shark	–	–	–	5	5		10

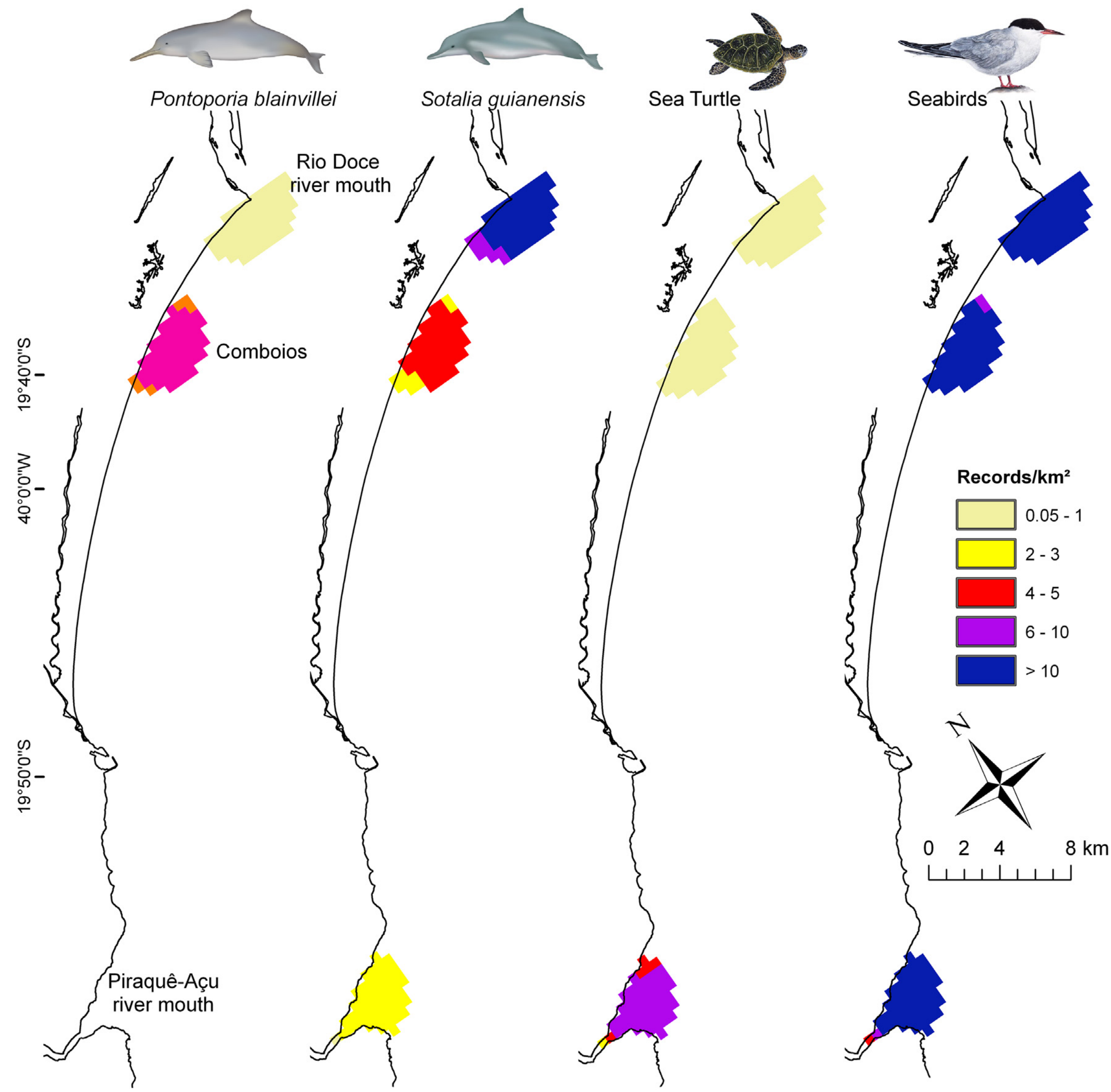

Fig. 3. Megafauna density in each of the locations monitored by drone (Rio Doce, Comboios and Piraquê-Açú).

the Rio Doce river mouth concerning the other sites monitored. The spring showed significantly lowest values recorded in the whole period and at all monitoring sites for marine and coastal birds (0.60 $\pm$ 0.89 sightings/km^2 at Doce River, 0.06 $\pm$ 0.10 sightings/km^2 at Comboios, and 0.01 $\pm$ 0.05 sightings/km^2 at Piraquê-Açu; Fig. 4). The Piraquê-Açu river mouth stood out with a significant increase in the average density of individuals in the winter and summer of 2020, showing 3.19 $\pm$ 3.81 and 3.61 $\pm$ 3.63, respectively. Different behaviors could not be thoroughly evaluated from drone observations, although foraging was possible to observe in all areas.

3.1.3. Population structure

3.1.3.1. Cetaceans. Calf and juveniles represented between 11% and 15% of all sightings of *S. guianensis* (Fig. 5). Franciscana (*P. blainvillei*) groups with calves and juveniles were present in 9% of the records in Comboios, and at the Rio Doce river mouth, 14% of the records found were of calves and/or juveniles (Fig. 5).

3.1.3.2. Sea Turtles. The proportion of juvenile sea turtles was high in all areas. We highlight the presence of 93% of juvenile green turtles in Piraquê-Açu, while in Comboios, 26% of the records are of adult loggerhead and leatherback (Fig. 5).

3.1.3.3. Seabirds. It was not possible to evaluate the age class of the birds during drone-monitoring.

3.1.3.3.1. ROV - habitat mapping. We identified seven (07) bottom types representing distinct marine habitats used by megafauna: mud; sand; sand with fragments; sand and mud; bryozoans, sponges and algae; reef structures; rhodoliths. The sand bottoms type “sand with fragments” is composed mainly of shells of benthic organisms and algae; and “sand and mud” have relatively finer sediment, interspersed by bands of fluid mud. The bottom type “bryozoans, sponges, and algae” has a predominance of sessile benthic invertebrates, interspersed by bands of coarse sand. The “reef structures” represent expressive reefs interspersed with sediment, sand, and gravel. The “rhodoliths” bottom represents large numbers of calcareous algal nodules on unconsolidated sediment. The “mud” bottom represents sediment finer than sand, often resuspended into the water column (Fig. 6).

The sites closest to the Rio Doce river mouth have bottoms dominated by mud. The presence of sand increases as one moves away from the coast, starting at 25 m depth. Near the southernmost drone-

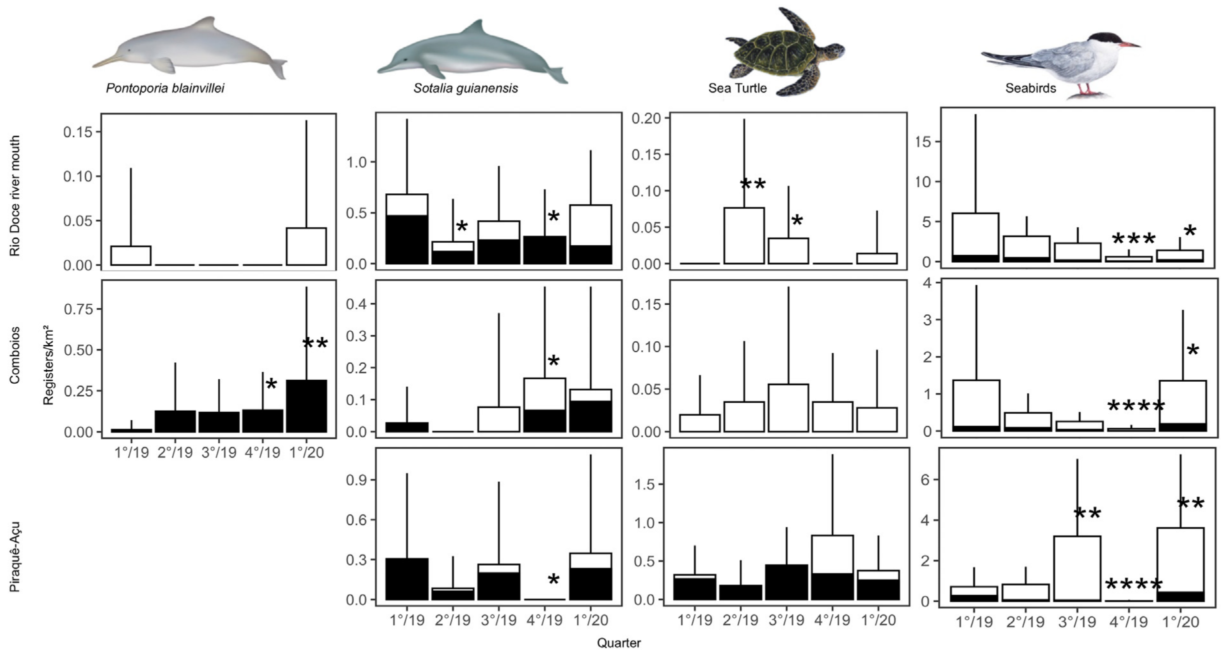

Fig. 4. Density of sightings grouped into quarters. The bar graphs use the quarterly average of the registered demand density, with the standard deviation. The black color in the bar graph refers to the foraging percentage among the registered groups. The number of asterisks represents the degree of significance of the differences ($p < 0.05$).

monitoring point, at the Piraquê-Açu river mouth, isolated rocky-reef structures are abundant, followed by sand and then bryozoan, sponge, and algal beds at greater depths.

4. Discussion

Data collected during the drone-monitoring and ROV sampling allow us to evidence patterns for evaluating effects related to the collapse of the Fundão dam in Mariana, Minas Gerais state. In addition, this study provides unprecedented information on groups and species of marine megafauna from hundreds of video records.

The Rio Doce river mouth supports the high density of the Guiana dolphin, especially during the summer months. This characteristic has also been registered near the estuary's mouth of Cananéia, where there is a higher density of *S. guianensis* during the rainy months (October to March), including the summer (Havukainen et al., 2011), showing a possible pattern of these animals approaching the coast during this period. Furthermore, Barros and Wells (1998) designate that the distribution and abundance of dolphins may be linked to the movements of prey, as observed in the present study, where the Rio Doce river region has a greater diversity and availability of prey.

The most common behavior in *S. guianensis* groups was feeding, which may be related to the high productivity found at and near estuarine mouths (Nixon et al., 1986). A study was done previously with stomach contents of individuals stranded on the eastern coast of Brazil, including at the Rio Doce river mouth, corroborates that the area is widely used for feeding (Rodrigues et al., 2020). This species also feeds in areas with coastal muddy shallows and muddy substrates in the bay of Paraty-RJ (Lodi, 2003), where it appears similar to those detected by the ROV.

In an unprecedented way, the franciscana feeding behavior was registered as predominant in the region, confirming the importance of this habitat use by this critically endangered species. In the diet of both cetacean species, fish are present, mainly Sciaenidae associated with estuaries. Cephalopods and crustaceans are also present. (Danilewicz et al., 2002; Daura-Jorge et al., 2011; Rupil et al., 2019). The feeding behavior of cetaceans was observed more frequently in the areas of the Rio Doce river plume.

The Espírito Santo *P. blainvillei* population is geographically isolated and the smallest population of the species (Siciliano et al., 2002; Danilewicz et al., 2012), as such it is called Franciscana Management Area Ia (FMA Ia; Cunha et al., 2014). In 2006, Frizzera et al. (2012) conducted a visual census for cetaceans from a boat at the Rio Doce river mouth, which registered no records of franciscana. An mtDNA analysis confirmed the existence of a genetic gap in the distribution of the franciscana, suggesting the population is highly threatened (Cunha et al., 2014). Local strandings, however, have been expressive in recent years, potentially reaching 12.9% of population mortality per year (Mayorga et al., 2020).

The percentage of calves or juveniles (11% to 15%) in the age composition of Guiana dolphins was similar among the sites monitored and similar to Frizzera et al. (2012) study. Additionally, they found a similar value with 20% of juvenile dolphins in a visual census study from a boat at the Rio Doce river mouth. For franciscana, the percentage of calves or juveniles was 9% to 14% of the records, showing these animals' presence in the coastal region. In Argentina, studies have already shown that female franciscana with calves are associated with shallow waters and occurrences in the spring and summer period (Bordino et al., 1999), as seen in our monitoring, especially at the Rio Doce river mouth where the groups were only present in the summer period (first and the fifth trimester analyzed).

It is challenging to observe sea turtles when they are at sea. Therefore, even with the use of the drone, our conclusions on their behavior are incipient. Most records were of *Chelonia mydas* (green turtle) and always of juvenile individuals of that species. Feeding behavior was most frequent at the Piraquê-Açu river mouth, possibly because Rio Doce and Comboios areas offer a low opportunity for macrophyte grazing. Green turtles are recruited to the coastal environment of Espírito Santo between the 2nd and 4th year of life (Barreto, 2017; Lenz et al., 2017), usually using this environment for foraging (Santos et al., 2015). Adult turtles (loggerhead, leatherback and, olive ridley) were recorded only in the areas closest to the Rio Doce river, which are known as a main reproductive site in the western South Atlantic, mainly for *C. caretta* (Baptistotte et al., 2003) and *D. coriacea* (Thome et al., 2007).

Species identification and age classification are difficult for seabirds recorded with the drone since most individuals are in flight. Sternidae, or Tern birds, were the most abundant in all monitored areas. Their

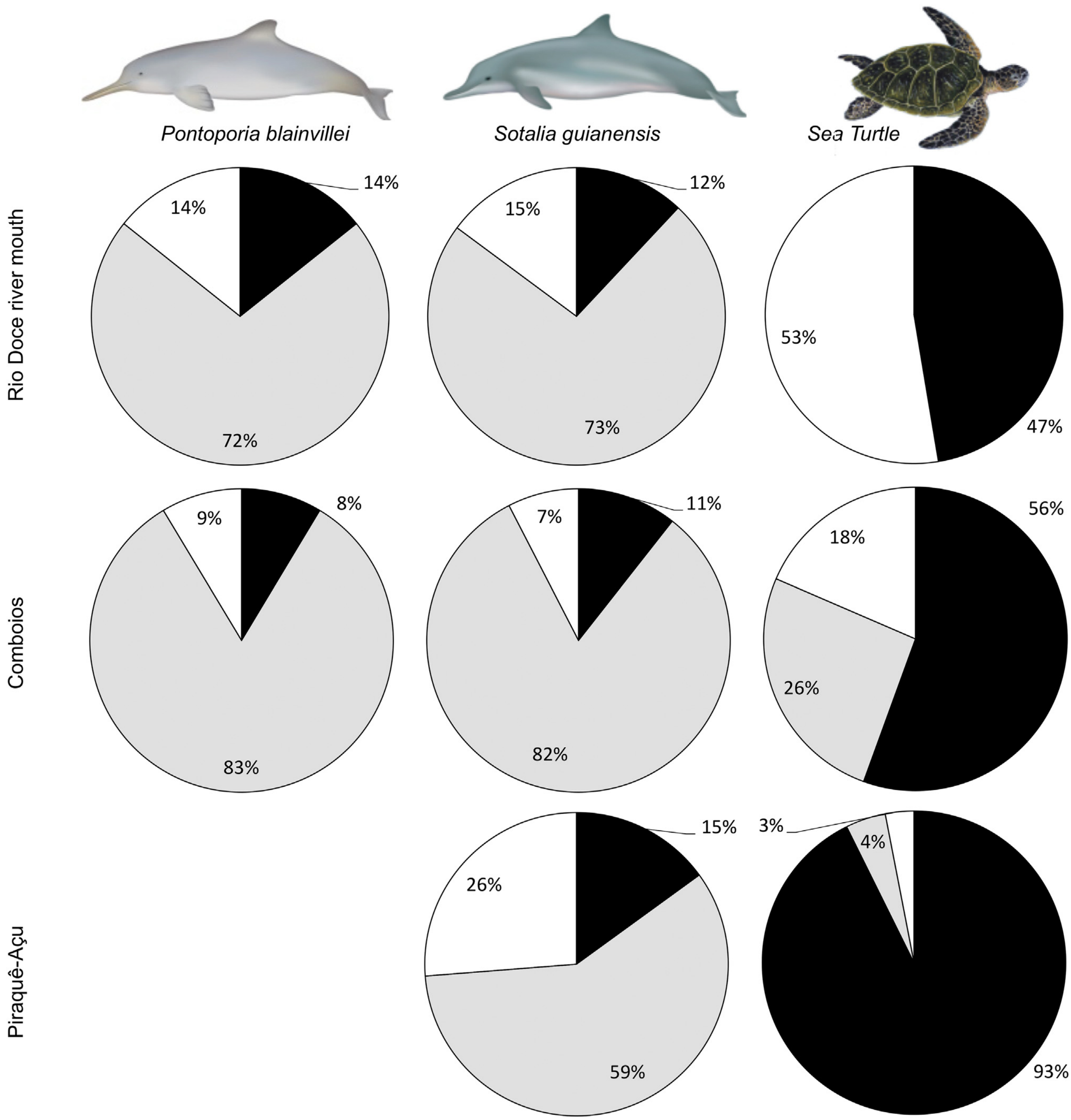

Fig. 5. Population structure of megafauna groups in each of the sampled areas of the taxa that obtained sufficient sightings for analysis. The pie chart represents the percentage of calf or juvenile records.

highest abundance occurred in January 2019 due to the presence of flocks of 200+ individuals landing on sand islands at the Rio Doce river mouth. The following decrease in species abundance during the southern hemisphere winter can be considered normal since the migration to the northern hemisphere is common, often for reproduction (Mestre, 2007; Somenzari et al., 2018).

All areas of megafauna concentration were ROV-mapped, thus allowing a better understanding of the habitat substrate preferences presented by the various groups. Small cetaceans, for example, primarily use areas with muddy bottoms, while sea turtles prefer regions with a rigid substrate, such as the forgotten reefs or the Environmental Protection Area (APA) Costa das Algas. The region immediately south of the Rio Doce river presented the highest concentration of megafauna and a hotspot for the conservation of endangered marine tetrapods.

This same region (immediately south of the Rio Doce river) is the coastal area most affected by the rupture of the Fundão dam. The area is considered highly fragile, with very high iron, aluminum, chromium, and manganese concentrations in water and sediments (ANA, 2016; Gomes et al., 2017). High concentrations of dissolved metals, including heavy metals, can alter sounds from the environment, causing cetaceans to require adaptations of their biosonar system (Frainer et al., 2016). On the other hand, adult sea turtles use the intertidal period, while juveniles use the area for feeding. Seabirds approach the coast searching for food and use the islands at the Rio Doce river mouth as a landing

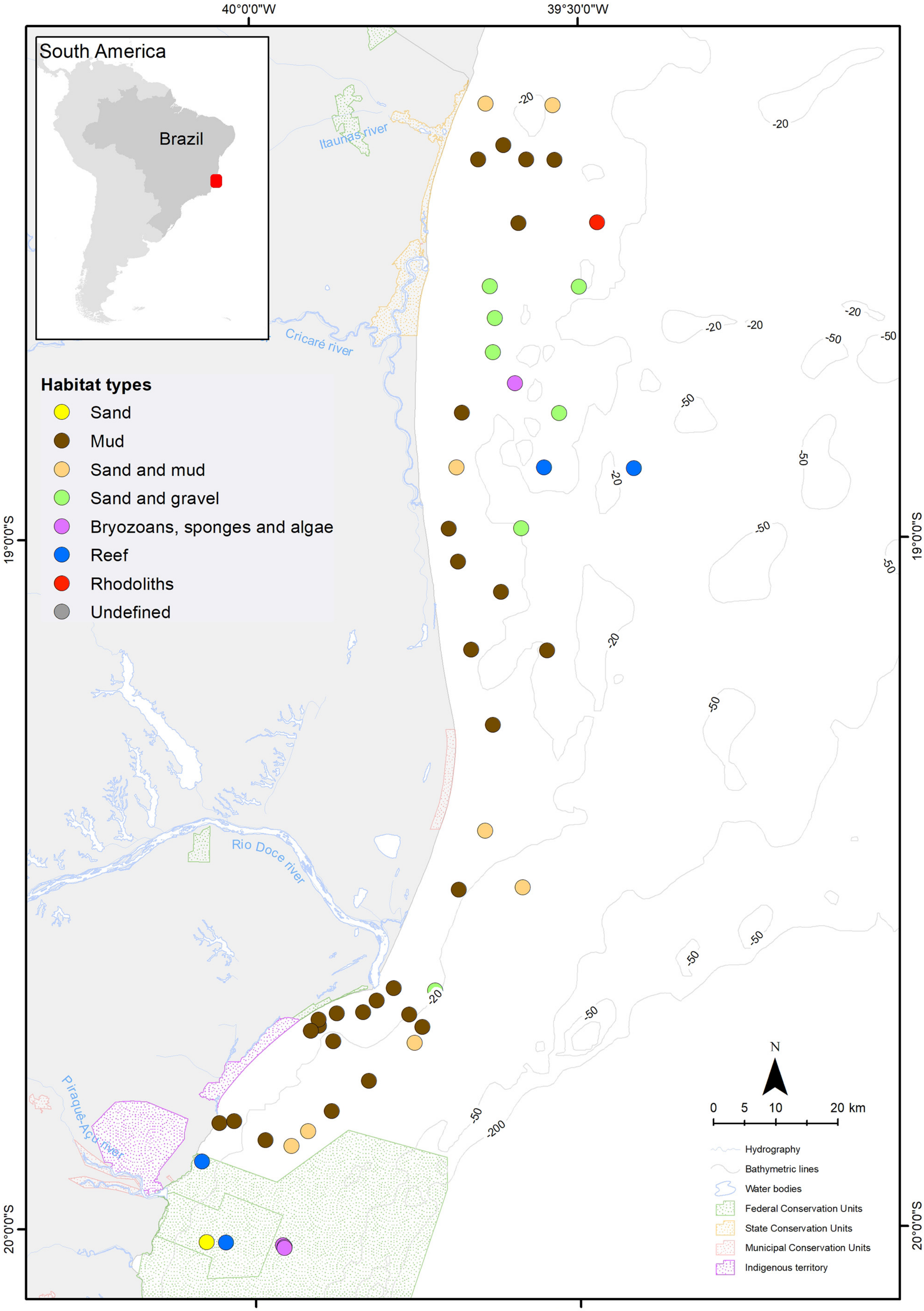

Fig. 6. Button types identified from ROV images.

point. Small cetaceans feed and raise their young throughout the year, with higher concentrations during the summer (Flach et al., 2008).

The last main report on the results of monitoring biodiversity associated with the Mariana disaster (RRDM, 2019) identified four hotspots of marine megafauna use in areas affected by tailings from ore. The main area impacted by tailings is in the coastal region located 30 km south of the Rio Doce river mouth (Marta-Almeida et al., 2016). The existence of these hotspots confirms these areas' vulnerability and an additional threat factor for these populations, some of which have a high degree of endemism and isolation.

5. Conclusions

The Rio Doce river mouth region proved to be extremely important for several species of marine megafauna. The months of January, February, and March (summer or late rainy season) stood out in greater species richness and abundance. This pattern is probably related to the high outflow of the Rio Doce river, nutrient inputs into the coastal zone, and, thus, the availability of food. The use of disruptive technologies and systematic monitoring allowed us to understand the local dynamics of populations, the preferences for habitat use, and access information not provided by traditional methods. However, to detect possible variations in abundance or behavior, long-term studies using comprehensive and reproducible methods, including evaluating marine sound, are fundamental. Analyses carried out with drone-monitoring and video-monitoring of habitats will establish causal links with possible sources of chronic impacts on marine megafauna affected by the dam failure. The coastal region affected by the disaster represents an additional focus of vulnerability with the conservation of threatened megafauna due to the significant aggregation and use of the most impacted areas.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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