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Integrating Different Types of Knowledge to Understand Temporal Changes in Reef Landscapes

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Reefs are highly diverse ecosystems threatened by anthropogenic actions that change their structure and dynamics. Many of these changes have been witnessed by different reef users who hold specific knowledge about the reefscape according to their experiences and uses. We aimed to understand whether fishers, divers, and reef scientists have different perceptions of general changes that have occurred in reefs and whether their knowledge converge, diverge or are complementary. We conducted 172 semi-structured interviews with stakeholders from Northeast and Southeast Brazil where either coral or rocky reefs occur, comprising most reefs occurring in the Southwestern Atlantic Ocean. Reef scientists and divers perceived corals have undergone the sharpest declines among reef species and indicate pollution and tourism as the major negative impacts on reefs. On the contrary, fishers noticed greater declines in fishing targets (i.e., groupers) and have hardly noticed differences in coral abundance or diversity over time. Divers had a broader view of changes in reef organisms, with some level of convergence with both reef scientists and fishers, while reef scientists and fishers provided information on more specific groups and economically relevant resources, respectively. The different stakeholders generally agree that reefscapes have undergone negative changes including diversity loss and abundance declines of reef organisms. The complementarity of information among different stakeholders enables a better understanding of how human behavior impact and perceive changes in natural ecosystems, which could be essential to manage reef environments, particularly those without baseline data.

Keywords: stakeholder perceptions, Brazilian reefs, environmental perception, random forest, Southwestern Atlantic reefs, recreational divers, artisanal fishers, marine scientists

INTRODUCTION

Humans have depended on coastal reef resources for millennia (Cinner et al., 2018). The dependency and interactions between people and reefs (i.e., economic and cultural) may vary greatly over time, within and among social groups. Certain groups of people may be more dependent on reefs than others, which may also vary through time or seasonally (Costanza, 1999).

The interactions between human populations and reefscapes happen through different stakeholders (Marshall et al., 2018), for example, institutional agents responsible for ordering reef use, non-governmental organizations that focus on reef conservation, reef scientists interested in understanding how reefs work, and people that make direct use (extractive or not) of reefs, such as fishers, tourism operators, diving companies, and tourists.

These stakeholders may have different and/or complementary perceptions of the reefs depending on the type and frequency of their use (Eddy et al., 2018). Regular users can pay attention to different characteristics of these environments depending on how they use and access them, which would explain why people have contrasting memories of changes in natural environments (Hicks et al., 2013). For example, there is strong evidence that fishers have detailed knowledge about temporal changes in their target species (Johannes et al., 2000) but do not notice declines in species with less or none economic importance (Damasio et al., 2015). Divers may perceive differences in biological attributes such as fish richness and coral cover, as well as in the structural complexity of coral reefs (Uyarra et al., 2009) and scientists may restrict their perceptions to their particular study target (e.g., fishes or corals).

Reconciling knowledge from different stakeholders, of variable age groups and experiences is an alternative to reconstruct the process of change that a particular species or environment gone through (Hansen et al., 2006). This could be an important tool to reconstruct sensitive reefscapes in areas that lack baseline data and struggle with research funding, management, and enforcement. This is the case of Southwestern Atlantic reefs, most of which are within Brazilian territory, occurring between the latitudes ∼5°N and 27°S and are marked by high species endemism of corals and fishes (Leão et al., 2016; Francini-Filho et al., 2018). These reefs are not homogeneous (Aued et al., 2018), while some of them are similar to typical coral reefs (Northeast region), others consist of rocky reefs that can support coral assemblages (Southeast and South regions; Leão et al., 2003). Brazilian reefs are found in shallow margins close to the coast, island edges and isolated banks (Leão et al., 2003; Kikuchi et al., 2010), many of them are close to densely populated areas where they are more subjected to direct anthropogenic impacts (Moura, 2000; Magris et al., 2021). Brazilian reefs are generally used for both extractive (i.e., fishing) and non-extractive activities (i.e., tourism, recreational diving, and scientific research), and these uses are often more intense when reefs are closer to the shore. Fishing, climate changes and pollution are among the main threats to Brazilian marine biodiversity (Magris et al., 2021), which combined may have caused severe changes in reef biodiversity.

We aimed to understand whether fishers, recreational divers, and reef scientists who use Brazilian reefs have a different perception about potential changes these reefs have undergone and whether they tend to converge or diverge on specific aspects of change. By unraveling, recognizing and connecting these perceptions we may be able to produce a more accurate historical reconstruction of changes and their magnitude in these ecosystems.

MATERIALS AND METHODS

This study was conducted between June 2018 and October 2019 in seven states along 3,133 km of the Brazilian coast (**Figure 1**), an area that comprises more than 50% of the distribution of reefs and diverse reef structures in Northeast and Southeast Brazil (Leão et al., 2016; Aued et al., 2018). The interview procedures were approved by the Ethics Committee at the Federal University of Rio Grande do Norte (CAAE: 73739917.3.0000.5537) and, in the case of protected areas, by the Brazilian System for Authorization and Information on Biodiversity (SISBIO: 65379).

Interviewed Stakeholders

We interviewed the stakeholders who make direct and constant use of reefs, namely fishers, recreational divers, and reef scientists. Among fishers, we focused on those who practice spearfishing to ensure a closer contact with the reefs, although we eventually included some fishers who use gillnets and hook-and-line, provided they were specialists in reef fishing. Despite not having a daily contact with reefs, recreational divers tend to have a unique and contemplative view of reefscapes because of the cultural values attributed to this leisure activity (Arin and Kramer, 2002), therefore we interviewed recreational divers and diving instructors. Among reef scientists, we focused on those whose research is focused on understanding reef ecological processes as we were interested in observable changes in living organisms. Despite our effort to find individuals within each of these groups of stakeholders (fishers, divers, and scientists) in every state we visited, we were unable to include representatives from all three categories in all states, either for logistical reasons and/or ease of access to certain groups. For example, in the state of Paraíba, we were only able to interview divers (**Figure 1**).

Data Collection

First, we identified key informants as leaders of fishing organizations, diving companies and recreational divers, and acquainted professors at universities known to at least one of the authors. From this initial list, we used the "snowball" technique, in which the key informants indicated people who they deemed relevant to contribute with the requested information (Goodman, 1961). These new informants named successive ones until we exhausted names or our capacity to reach them. Opportunistic interviews were also conducted with stakeholders who fit the criteria to answer the questionnaire. All interviewees exclusively answered about the reefs locations they had experience with throughout their lives. The interviews were conducted in two ways: in-person and using online forms. The online form was mainly used to reach divers, although some reef scientists also used this platform due to the difficulty of arranging face-to-face meetings.

The questionnaire was divided in three sessions (**Table 1**): "Personal data and impressions" in which we collected information on stakeholders' age, experience, reef region, among others; "Historical knowledge" in which we were interested in identifying the stakeholders' perception of organisms that decreased or increased in reef landscapes; and "Abiotic environment and threats" in which we asked

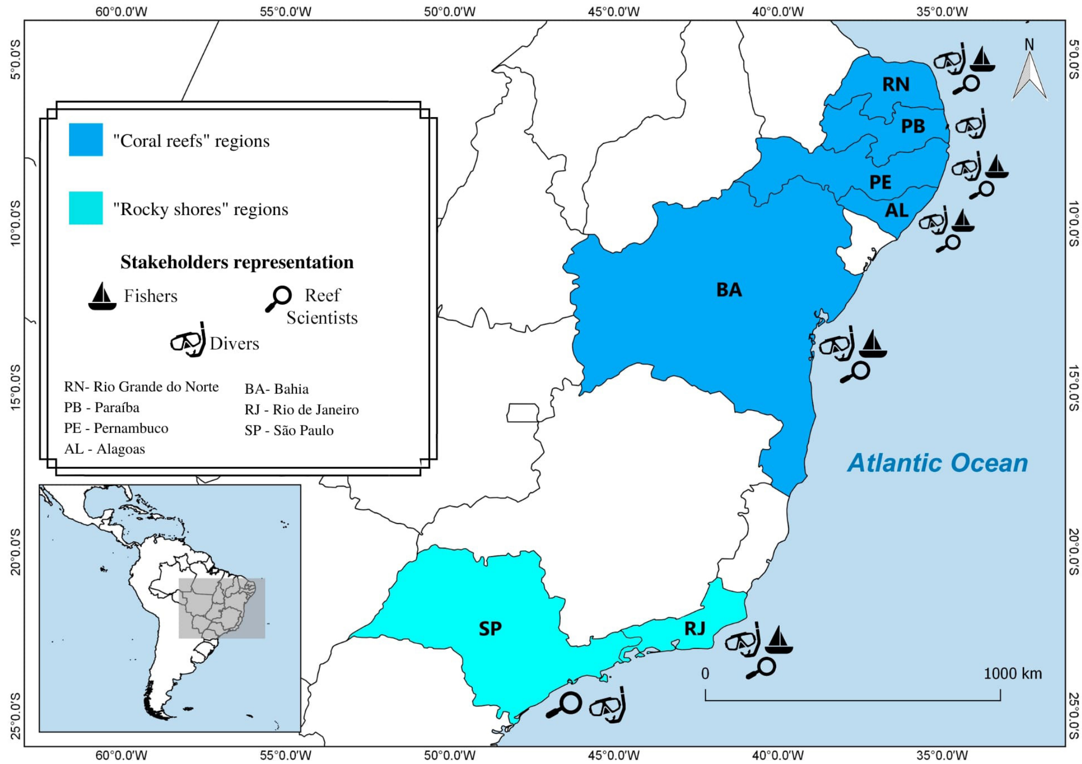

FIGURE 1 | States, where stakeholders were interviewed, are highlighted and divided between the region where coral reefs (states in darker blue) and rocky reefs (states in light blue) are found. It is shown which stakeholders were interviewed in each state: fishers with a sailboat, divers represented with a snorkel, and reef scientists symbolized with a hand glass. The map on the bottom left showing South America, localizing Brazil.

interviewees about changes in water and climate, how they perceived the pollution, and impacts in reef landscapes. We included in the questionnaires organisms that are conspicuous to the benthic (Aued et al., 2018) and fish communities (Morais et al., 2017), and that are perceived to be more subject to changes (**Supplementary Table 1**). We presented photographs of these organisms to the interviewees so that they could inform whether they knew the species and whether they had noticed changes in their abundance. Respondents were also free to list other species or groups of organisms for which they noticed changes in abundance. All data will be available upon reasonable request to the authors.

Data Analysis

In order to assess the agreement between and within the groups of stakeholders we combined three analytical methods: Random Forest (RF), Permutational Analysis of Variance (PERMANOVA) and Non-metric Multidimensional Scaling (NMDS). The RF is a supervised learning algorithm (James et al., 2013) that randomly creates a forest, combining decision trees to obtain predictions with greater accuracy and stability (James et al., 2013). The RF was used herein for two main purposes: (1) to understand how the different variables contribute to define a group of stakeholders (i.e., perceiving changes in abundance in a specific group) through the accuracy and Gini value; and (2) to assess how cohesive each stakeholder group is in their perceptions through a confusion matrix. The accuracy and Gini indicators designate which variables define the groups (fishers, divers, and reef scientists). The confusion matrix is obtained using the "out-of-bag" forecast for each observation in the training set of trees (Cutler et al., 2012). The variables with the highest number of mentions by stakeholders in each category (two models: decrease and increase) were chosen to compose the RF model (**Table 1**). All variables contained in the "Abiotic environment and threats" component and the "Environmental health" variable were used for the characteristics of the "Abiotic environment and impressions" block (**Table 1**). PERMANOVA and nMDS were used to test and visualize the groups formed by organisms which have decreased and organisms that have increased (**Table 1**). The PERMANOVA was used to assess if the dispersion of the stakeholders' responses is different among the three groups (Anderson, 2017). The nMDS based on Jaccard distances was used to visualize the outputs of the RF allowing to assess the qualitative interrelationships between the variables and to define which variables were most related to each stakeholder group. The number of axes in the nMDS was chosen to maintain the stress value below 0.15 and ensure that any existing patterns in the data would be captured by the multidimensional ordination space. All analyzes were performed using the RStudio v interface 1.2.5033, an integrated development environment for R program (R Core Team, 2019), using the "randomForest" (Liaw and Wiener, 2002), "factoextra" (Kassambara and Mundt, 2017),

TABLE 1 | Variables used in the study organized into three different components with their description, types, and analyses performed.

Components	Groups and variables	Description	Variables types	Analysis
Personal data and impressions	Stakeholder	Type of stakeholder. "Fisher"; "Diver," and "Reef scientists"	Nominal	Descriptive
	Age	Stakeholder's age (years)	Discrete	Descriptive
	Experience	How long the stakeholders have been engaged in research, fishing, or diving (years)	Discrete	Descriptive
	Initial and final contact	Years of initial and final contact with the chosen reef environment (year)	Discrete	Descriptive
	Environmental health	Regards the first and last contact with the environment, evaluated in the following categories: excellent; good; median; bad; and terrible. Divided into two categories: "initial health" and "recent health"	Ordinal	Random Forest
Historical knowledge	Organism decrease	Species the stakeholders noticed which have decreased in the reef environment	Nominal	Descriptive
	Organism decrease groups	Number of mentions per stakeholder for each category of organisms that have decreased It includes the following variables: "Massive corals," "Branched corals," "Echinoderm," "Cartilaginous fish," "Epinephelidae fish" (groupers), "Labridae fish: Scarinae" (parrotfish), "Other reef groups," "Mollusks," and "Crustaceans"	Discrete	Random Forest and NMDS PERMANOVA
	Organism increase	Species that the stakeholders noticed that have increased in the reef environment	Nominal	Descriptive
	Organism increase groups	Number of mentions per stakeholder for each category of organisms that have increased Includes the following: "other reef groups," "Invasive," "Zoanthids," "Echinoderm," "Pomacentridae Fish" (damselfish), and "Algae"	Discrete	Random Forest, NMDS, and PERMANOVA
	New organisms	Exotic and invasive species	Nominal	Descriptive
Abiotic environment and threats	Water	Assessment of reef water turbidity: "More turbid"; "Less turbid"; and "The same"	Ordinal	Random Forest
	Climate	Changes that have occurred in the regional climate (open response)	Nominal	Random Forest
	Pollution	Perception of pollution of the reef environment: "More polluted"; "Less polluted"; and "The same"	Ordinal	Random Forest
	Impacts	The three main threats to reef landscapes in order of importance	Nominal	Random Forest

"FactoMineR" (Lê et al., 2008), "vegan" (Oksanen et al., 2019), "ggplot2" (Wickham, 2016), "grid" (R Core Team, 2019), and "ggrepel" packages (Slowikowski, 2019).

RESULTS

Stakeholders' Profile

Fishers

Fishers formed the oldest (average = 49 yo) and most experienced group of respondents (~33 years of career; **Table 2**), providing approximately six decades of perceptions about the changes in Brazilian reefs. Most of them were spearfishers (71.0%), although some fished with gillnets (20.2%), and hook-and-line (8.7%). Fishers made 297 citations of organisms that they perceived as having declined (**Table 2**), but 29 of them were disregarded as they did not refer to species necessarily dependent on reefs (i.e., manatees). Likewise, six mentions of organisms that fishers perceived as having increased were disregarded for referring to cetaceans.

Among the organisms perceived by fishers to have decreased, the most cited groups were parrotfish ("Labridae: Scarinae," 36.1% of the fishers citations), followed by groupers ("Epinephelinae," 52.1%), sharks and rays ("Cartilaginous," 55.95% of fishers citations; **Figure 2A**). Among the organisms perceived to have increased, sea turtles stood out with 64.6% of the citations (**Figure 2B**). Only nine fishers mentioned the presence of new organisms, which exclusively referred to the sun coral (*Tubastraea* spp.). Most fishers said they believe reefs became more polluted (56.5%) and more turbid (68.1%) in comparison to the beginning of their career. About 55% also noticed changes in the local climate over their years of experience. Fishers also indicate industrial fishing as the main threat to reefs.

TABLE 2 | Main qualitative results according to the interviewed stakeholders (fishers, reef scientists, and divers).

	Fishers	Divers	Reef scientists
No. of interviews	69	60	43
Age (with standard deviation)	49 years (mean) 25 to 75 years (± 10.2)	35 years (mean) 21 to 54 (± 8.6)	45 years (mean) 24 to 80 years (± 13.0)
Experience (with standard deviation)	33 years (mean) 10 to 63 years (± 12.2)	15 years (mean) 1 to 42 years (± 11.08)	20 years (mean) 4 to 48 years (± 12.01)
Organisms that decreased (citations)	297 (4.3 per person)	336 (5.6 per person)	213 (5 per person)
Organisms that increased (citations)	126 (1.8 per person)	78 (1.3 per person)	107 (2.8 per person)
Reef threats (main answers %)	Industrial fishing (44.9) Tourism (17.4) Divines reasons (14.5)	Climate change (55.9) Pollution (48.3) Tourism (33.3)	Fishing (27.5) Tourism (27.5) Pollution (22.5)
Pollution % (more polluted)	56.5	68.3	74.4
Water % (more turbid)	68.1	35	37.2
Climate change % (noticed any change)	33.3	43.7	20.9
Environmental health – beginning (main answers %)	Great (72.5) Good (11.6)	Great (45) Good (38.3)	Intermediate (51.2) Good (30.2)
Environmental health – currently (main answers %)	Bad (46.4) Horrible (43.5)	Intermediate (38.3) Bad (35)	Intermediate (53.4) Bad (27.9)

Divers

Divers formed the youngest and least experienced group (35 years old, 15 years of experience, on average), but even so, they were the ones who cited the highest number of organisms that have declined (N = 336; **Table 2**). Similar to other stakeholders, divers highlighted the decline of "Massive corals" (55.31% of divers' citations) followed by parrotfish ("Labridae: Scarinae"; 42.6%), (**Figure 2A**). On the other hand, divers also noticed an increase in damselfish ("Pomacentridae"; 37.9% of divers' citations), "Zoanthids" (34.8%) and "Algae" (27.2%) (**Figure 2B**). Divers also indicated the appearance of new organisms, with 11 mentions of the sun coral (*Tubastraea* spp.) and six mentions of other organisms including algae, mollusks, and the lionfish (*Pterois volitans*). Most divers believe that water turbidity (65%) and climate (56.3%) have not changed since the beginning of their experiences in the past decades. On the other hand, most divers suggested that the reef environment became more polluted, sustain an intermediate health status (**Table 2**), and indicate climate change as the major threat to reefs.

Reef Scientists

Reef scientists were on average 45 years old and a maximum of 20 years of experience (**Table 2**). Similar to fishers, reef scientists also noticed declines of parrotfish ("Labridae: Scarinae"; 21.3% of the reef scientists' citations), and "Massive corals" (42.5%) (**Figure 2A**). They also noticed an increase in "Sea turtles" (24.4% of citations) and "Zoanthids" (46.5%) (**Figure 2B**). Ten reef scientists (23.2%) also noticed the presence of new organisms in the reef landscapes, especially the sun coral (*Tubastraea* spp.; 10 mentions). The other new organisms mentioned (N = 14) included octocoral species, ascidians, lionfish (*P. volitans*), sponges, the polychaeta *Branchioma* spp. and the ophiuroid *Ophiothela* spp. Most reef scientists (74.4%) suggested that reefs are now more polluted and some of them (37.2%) indicated that the water is more turbid in comparison the beginning of their careers. Most of them also chose not to give their opinion on the impact of climate changes on reefscapes. Reef scientists see fishing as the main threat to reefs and have more conservative opinions on general reef health classifying it as intermediate but stable since the beginning of their careers (**Table 2**).

Agreement Among Stakeholders

The three groups of stakeholders share a general perception that the reef health has deteriorated over time. About 46% of fishers classified the current reef health as "bad," 53.4% of reef scientists and 38.3% of divers classified as "intermediate" (**Table 2**). Regarding the general and abiotic aspects of perception (first random forest analysis), the three groups of stakeholders differ in how they evaluate the "Initial health," "Recent health," and the "Impacts" sources (Random Forest: accuracy 63.4%) (**Figure 3A**). Divers and reef scientists showed less homogeneous responses within each group, with 50% and 34% being mistakenly classified as belonging to another group of stakeholders, respectively (**Supplementary Table 2**). Most fishers were recognized as such

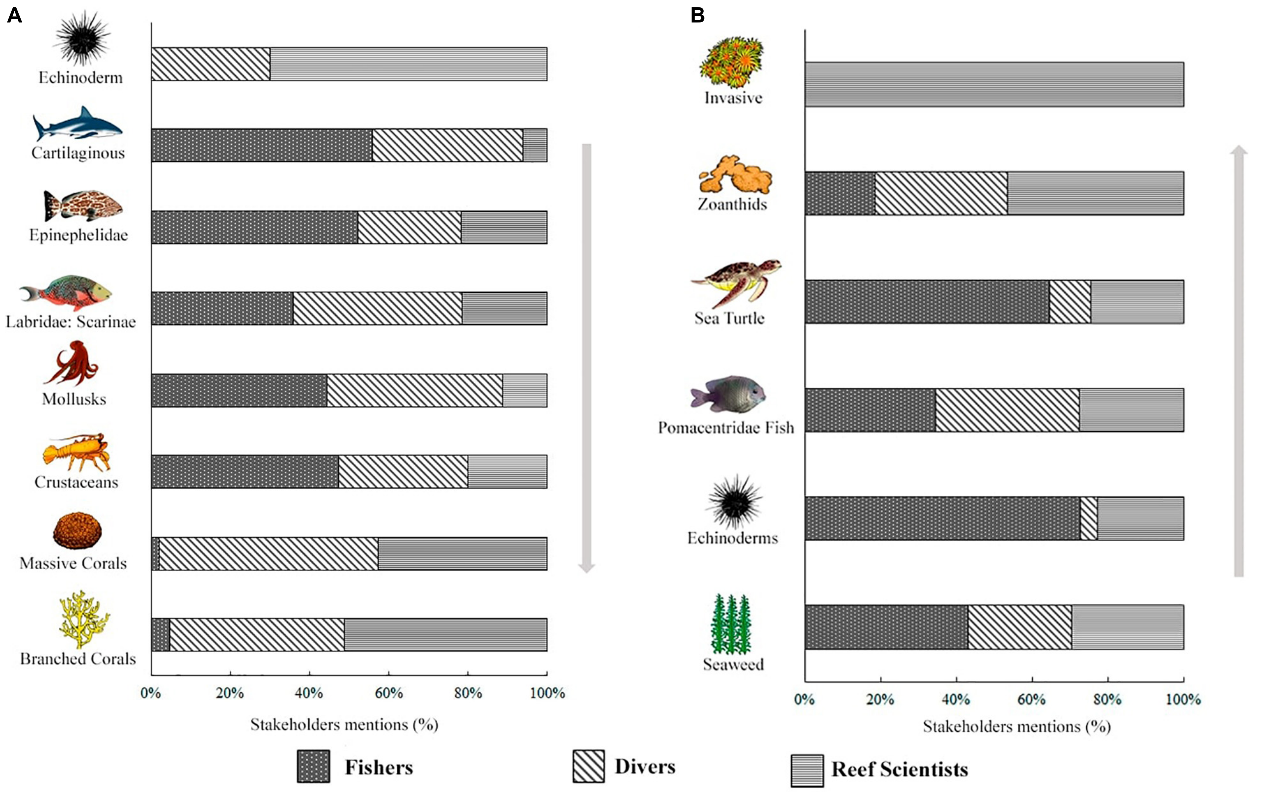

FIGURE 2 | Main organisms mentioned by fishers, divers, and reef scientists as having decreased **(A)** or increased **(B)** in the Brazilian reef landscapes in the last six decades. Only organisms that had a minimum of 5% in each group of citations were included among the total citations of increase and decrease, respectively. The down arrow on the left represents the organisms that declined, and the up arrow on the right represents the organisms that increased in reef landscapes.

(74%), 21.7% were recognized as divers, and 4.3% as reef scientists. About 50% of the divers were recognized as such, 26.6% as fishers and 23.3% as reef scientists. Among the reef scientists, 65.1% were recognized as such and 27.9% as divers (**Supplementary Table 2**).

Regarding the species that stakeholders perceive to have declined (second random forest analysis), their main differences were on the groups "Massive Corals" and "Epinephelidae Fish" (Random Forest: 63.4% accuracy; **Figure 3B**). The fact that fishers mostly perceive decreases in fish-related organisms, such as parrotfishes and groupers made them significantly different from the other stakeholders (PERMANOVA p-adjusted (0.003; **Supplementary Table 3**), who tended to mention massive corals more often (**Supplementary Tables 2**, **3**). Reef scientists were highly mixed with the other stakeholders in the Random Forest: 53.5% were identified as divers and 13.9% as fishers. Specifically, most fishers were recognized as such, but 18.8% were recognized as divers. Most divers were also identified as belonging to their own group, however, 18.3% were recognized as fishers and 15% as reef scientists (**Supplementary Table 2**). These trends were confirmed by the nMDS analysis, which showed that fishers tended to mention more "Cartilaginous Fish" and "Epinephelidae Fish" compared to the other stakeholders (**Figure 4A**). In turn, reef scientists and divers tended to mention "Massive corals," "Echinoderm," and "Branched corals" (**Figure 4A**).

The most important factors separating the stakeholders for species which were perceived as having increased are "other reef groups," "Invasive" and "Echinoderm" groups (Random Forest: accuracy 59.9%) (**Figure 3C**). In this case, all groups of stakeholders were significantly different from each other (**Supplementary Table 3**). Again, reef scientists were the least recognized stakeholders by the model: only 39.5% were recognized as such, 46.5% were characterized as divers, and 13.9% as fishers, reinforcing the dispersion of information among these stakeholders (**Supplementary Table 2**). Most fishers and divers were identified as such, except for 37.7% of the fishers who were recognized as divers, and 25% of the divers who were characterized as fishers. In this specific nMDS, fishers were more associated through citations of "Sea turtle" groups, while reef scientists and divers were more associated to the citation of "Zoanthids" and "Invasive" groups (**Figure 4B**).

DISCUSSION

The three groups of stakeholders perceived changes in reef health and pollution, generally agreeing that many species declined in abundance. Because these groups had different perceptions regarding which species have declined or increased, combining their knowledge can help create a more comprehensive

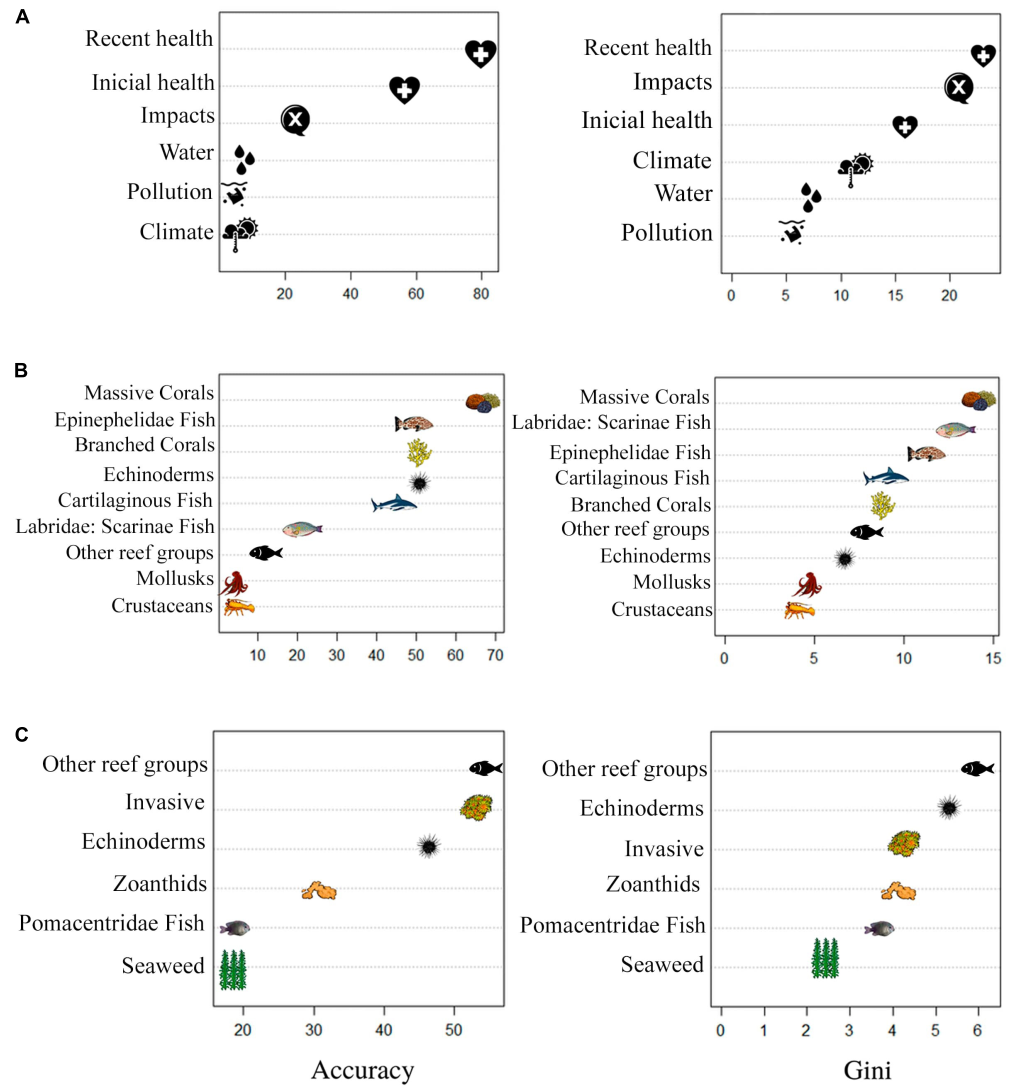

FIGURE 3 | Random Forest accuracy and Gini values showing the main variables responsible for the differences in stakeholder perception on. **(A)** Changes in abiotic reef environment. **(B)** Organisms that have decreased. **(C)** Organisms that have increased in reef landscapes. Notice that the higher the accuracy or the Gini value, the more likely it is that that variable contributed to separating the stakeholders according to their perceptions.

understanding of past changes in Southwestern Atlantic reefs. Stakeholders noticed changes in organisms related to their occupations. For instance, fishers mentioned decreases in targeted fishes, such as parrotfish, groupers, sharks and rays, including multiple species that have been overfished and in dire need of management (Giglio et al., 2014; Lessa et al., 2016; Roos et al., 2020). They also indicated a great decrease in shark species within the genus *Sphyrna* spp. and particularly the species *Ginglymostoma cirratum* between the 1980s and 1990s (Leduc et al., 2021), and in the locally important black grouper *Mycteroperca bonaci* (Bender et al., 2014). Parrotfish decline have started in the 1990s, although the exploitation of some species, such as *Scarus trispinosus*, may have started in the mid-1980s in some parts of the country (Bender et al., 2014). Divers and reef scientists noticed coral declines more frequently than fishers probably because they are more likely to pay attention to the reef substrate and sessile invertebrates due to their recreational and scientific interest, respectively (Giglio et al., 2015). This perception is corroborated by the increase in coral mortality due to more frequent and intense thermal anomalies in addition to land-based stressors in Brazil (Teixeira et al., 2021). Reef scientists were also the only stakeholder group to notice a decline in sea urchin populations. Interestingly, fishers reported an increase in the abundance of black urchins. Sea urchin declines were largely documented in the Atlantic Ocean, such as the emblematic case of *Diadema antillarum* that almost disappeared after a massive die-off caused by a disease in 1983–1984, which is linked to increased algal abundance in many Caribbean reefs (Hughes, 1994; Tuya et al., 2005). However, such decline noticed by scientists in Brazil probably had little to know effect on sea urchin

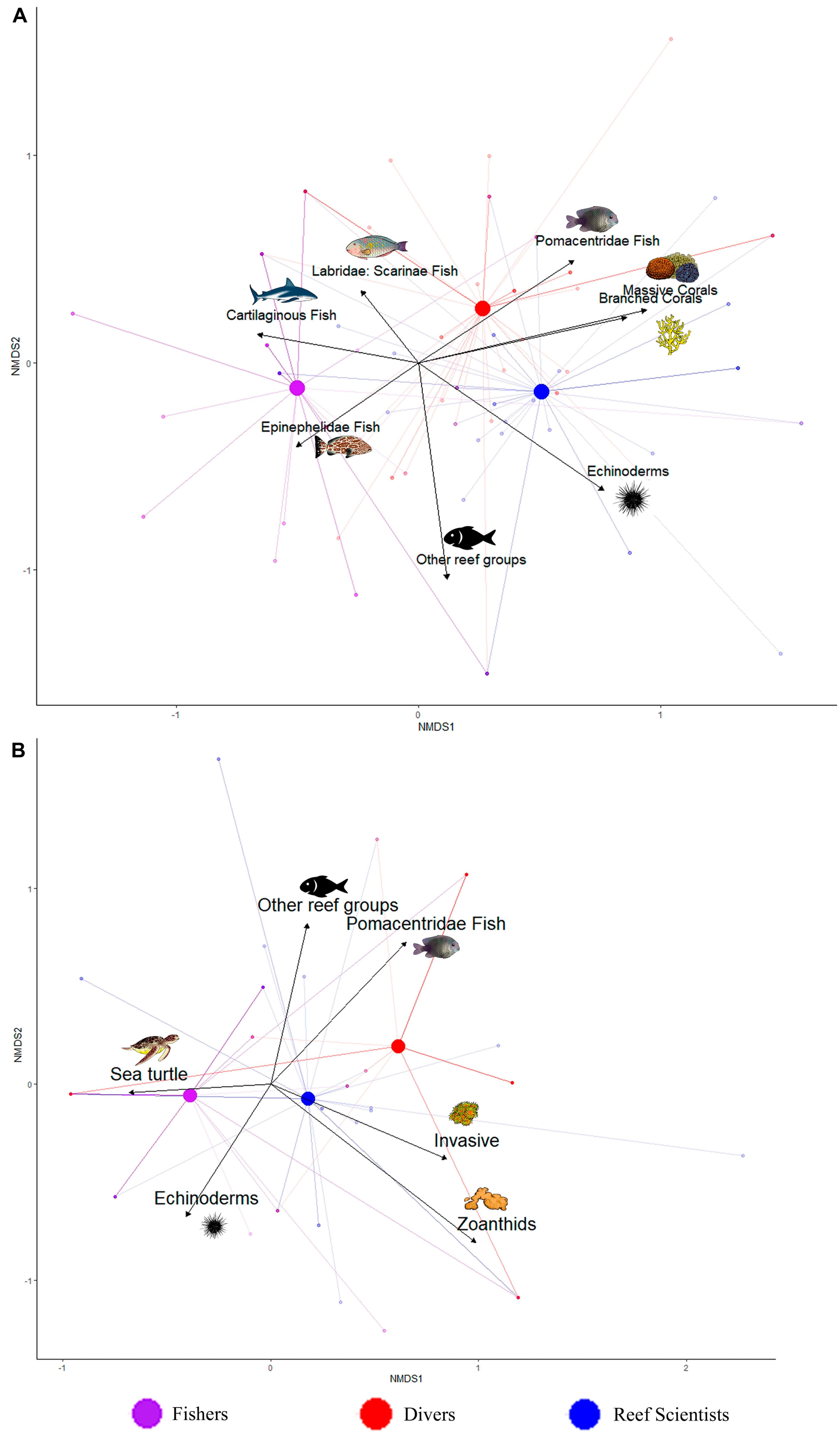

FIGURE 4 | Non-metric multidimensional scaling (NMDS) for organisms that have change in reef landscapes comparing the perception of the three types of stakeholders in the study: fishers, divers, and reef scientists. **(A)** Organisms that have declined ("stress value" = 0.12). **(B)** Organisms that have increased ("stress value" = 0.07). The stakeholders are represented through the colorful vectors, purple for fishers, red for divers, and blue for reef scientists. The black vectors represented the trend data for three types of stakeholders.

herbivory since current abundances seem to be enough to control macroalgal in shallow zones of subtropical reefs (Cordeiro et al., 2020). Stakeholders also have different perceptions on which organisms have increased in Southwestern Atlantic reefs. Divers mentioned the increase of organisms in shallow coastal reefs (i.e., Pomacentridae fish, zoanthids, and algae), an area often used by diving companies. Illegal feeding to attract fish and entertain tourists in some of these areas (Silva et al., 2020) may also have affected their perception of increase in abundance. Reef scientists mentioned reef organisms that increased but that were not on the original list (e.g., sponges) and were the only stakeholder group to spontaneously classify a species as invasive. Fishers mentioned an increase in sea turtle abundance more often than any other group of stakeholders, which may be directly related to a fishing ban established in the early 1990's (Marcovaldi and Marcovaldi, 1999) and to the numerous reports of bycatch in gillnets (Marcovaldi et al., 2006), increasing the contact between fishers and sea turtles. The recovery in sea turtle populations can also be attributed to a massive protection of sea turtle nests in Brazil for over 30 years (Marcovaldi and Chaloupka, 2007). Mentions of new organisms was rare regardless of the stakeholder group, but when it occurred the sun coral *Tubastraea* spp. was the most cited organism. There is evidence that *Tubastraea* spp. have been spreading throughout Brazilian reefs, from the states of Ceará (3°S) to Santa Catarina (∼27°S), being a major problem in rocky reefs of Southeastern Brazil (Riul et al., 2013; Capel et al., 2019). Indeed, the sun coral may significantly change the reef community, since experimental competitive interactions between the invasive *Tubastraea tagusensis* and the native coral *Siderastrea stellata* caused significant damaged and mortality in the native species (Miranda et al., 2016).

Fishers were generally more pessimistic about the current health state of reefs, which may be related to the decline in stocks of their fishing targets, but also to the fact that they use reefs and the oceans more often than any other user. Divers also classified the current reef health as "bad," which is likely due to their greater contact with touristic sites, which tend to be more degraded compared to those far from the coast (Hannak et al., 2011). Reef scientists were relatively more optimistic classifying reef health as "intermediate" or "bad." Although it is not possible to state the reason for this difference in perception among stakeholders, reef scientists use external references from the literature in addition to personal experiences to assess the health status of Brazilian reefs. Therefore, these unified opinions of reef health among scientists may exist because of their education and experience, that could even compensate the shifting baseline because of their formal knowledge (Muldrow et al., 2020). In addition, reef scientists are divers with scientific training and experience, and often interact with fishers or assess information provided by fishers (Bender et al., 2013), which could explain why their perception was mixed with those groups of stakeholder.

Different stakeholders also attributed different threats to the reefs that would help explain their current health status. We only interviewed artisanal fishers and they cited industrial fishing as an important impact on reefs. However, reefs are mainly fished by artisanal fishing, and some of its gear can indeed damage corals (Link et al., 2019) and cause significant impact to fish stocks (Bender et al., 2014). Denying that artisanal fishing activities can have negative consequences to reefs can hinder decision-making (Vaclavikova et al., 2011). For example, fishers may resist management measures, even those aimed at protecting endangered species, if they do not feel at least partially responsible for current reef health. Some fishers also highlighted that impacts on reefs happen for divine reasons, which suggests the difficulty and need to bring scientific information to these groups (Hilborn, 2007). Reef scientists also highlighted the negative impacts of fishing activity on reefs, specifically causing overfishing. Part of these reef scientists may be more aware of the impact of fisheries for being part of groups that assist the government in designing fishing regulations, so they may have access to more detailed fisheries information on a national level. These scientists are invited to these groups exactly for their expertise on the species and awareness of the stock status, these groups facilitate the exchange of information increasing their understanding of fishing impacts.

All groups perceived some level of negative impact of tourism on reefs, which is widely recognized in the literature (Giglio et al., 2017, 2020). Reef scientists are likely to deal with or be aware of impacts caused by tourism such as fish feeding, coral removal, and over-visitation (Liu et al., 2012). Fishers may have a conflict with tourism activities, including competition over space use (Outeiro et al., 2019). Divers may be especially aware of the impact of tourism because they are directly related to this activity (Neto et al., 2017), some of them are tour guides in reef environments and/or have great contact with tourism companies that often give or receive instructions to avoid their impacts on reefs. The fact that some divers understand the impacts of tourism, despite working in or promoting the sector, possibly suggests that they have been following reef degradation in areas increasingly subjected to visitation (Dearden et al., 2007). Conversely, divers can also be critical allies of science and conservation through their involvement in citizen-science programs that suggest divers without previous scientific training can provide reliable estimates of fish abundance (Vieira et al., 2020).

The increase in pollution was also perceived by most stakeholders, although especially by reef scientists and divers, who are more likely to visually notice it in reefs (Costa, 2007). Only divers rated climate change as the most important factor among reef threats. Perhaps divers are more exposed to this type of information through the media and social media than fishers, who tend to have low education levels and poor access to other social services. Divers are also possibly less afraid of expressing an unsupported opinion than reef scientists who do not work on climate-related issues. Scientists are experts in their specialism and expect to be recognized for it, which is probably why scientists do not want to express opinions about subjects outside their expertise (Myers, 2003). In fact, not even the consecutive cases of bleaching observed on the Brazilian coast (Dias and Gondim, 2016; Leão et al., 2019; Ferreira et al., 2021) seem to have been enough to make climate change an important issue to be raised here by reef scientists. A possible factor for this is the lower frequency of thermal anomalies in South Atlantic and particularly low post-bleaching mortality (<5%) when compared to the Pacific and Caribbean until recently (Mies et al., 2020). Climate change may also be difficult to be perceived on its own, especially when it is not easily associated to local climate events (Spence et al., 2011).

Overall, fishers provided more consistent responses. The interviewed fishers were precisely those who target species similar to the fish presented in the questionnaire. Fishers may also be immersed in a more culturally homogeneous world in small coastal communities than that shared by reef scientists and divers from different regions of the country (Reis and D'Incao, 2000). Unlike fishers, reef scientists have their specific interests diffused over a large set of reef species. Compared to the other stakeholder groups, reef scientists provided the least homogeneous responses, sometimes confused with those of fishers, but mainly with those of divers. Although many reef scientists are attentive to interspecific relationships, most are focused on particular groups of organisms and their opinions may only lean toward their research object.

Different stakeholder groups agreed with the changes in reef landscapes, but also share conflicting notions on specific subjects. This disagreement can represent an obstacle to governance and the management of natural resources (Yandle, 2003; Suárez de Vivero et al., 2008), but can also be a source of complementarity as each group perceive unique aspects of changes on ecosystems. Converging information reinforces the idea that some species or certain abiotic characteristics have undergone significant changes that are noticeable by all. By combining these perceptions, we gathered strong evidence that parrotfishes, groupers, sharks, and corals have undergone significant declines, whereas seaweeds, zoanthids and damselfishes have increased in Brazilian reefs. Pollution and fishing are major problems and reef health has suffered and overall decline. Such a scenario may jeopardize not only reef biodiversity but the benefit it provides to many people that depend on it for multiple uses. Combining different knowledge is an important step toward understanding the history of human-caused impacts on ecosystems, mitigating impacts, restoring key ecosystem functions, and preparing for the future.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee at the Federal University of Rio Grande do Norte (CAAE: 73739917.3.0000.5537) and Brazilian System for Authorization and Information on Biodiversity (SISBIO: 65379), with the latter specifically for research done in protected areas. Written informed consent for participation was not required for this study in accordance with the National Legislation and the Institutional Requirements.

AUTHOR CONTRIBUTIONS

MQ-A and GL conceived the idea and developed it with PL. MQ-A collected all the data. PL and GL contacted key participants for the interviews. MQ-A and FF performed the statistical analyses. MQ-A and PL wrote the manuscript with inputs from all co-authors and also designed the figures. All authors contributed with text revision and the final format of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.709414/full#supplementary-material

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