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Baseline

Retirement risks: Invasive coral on old oil platform on the Brazilian equatorial continental shelf

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ABSTRACT

The objective of this study was to report, for the first time, the presence of an invasive coral (*Tubastraea tagusensis*) in an oil platform on the Brazilian equatorial continental shelf. This structure is located more than 1200 km north from other oil and gas structures colonized by this coral. We also discussed the retirement and decommissioning of old biofouling-encrusted oil and gas platforms (~62 platforms) from decreased production and the current oil crisis, exacerbated by the COVID-19 pandemic. This presents an ecological concern due invasive coral range expansion and potential impacts to poorly studied ecosystems such as marginal shallow-water coral reefs and mesophotic ecosystems. It is imperative that mindful risk analysis and rigorous environmental studies must precede the installation of new oil and gas platforms. In addition, decommissioning of retired structures should take into consideration marine restoration and non-indigenous species dispersal, and more specifically, *Tubastraea* bioinvasion.

Tubastraea coccinea Lesson, 1829 and *Tubastraea tagusensis* Wells, 1982 are azooxanthellate scleractinians corals native in the Indo-Pacific Ocean (Paula and Creed, 2004, 2005; Creed, 2006) that have high invasive potential; their first records in the Western Atlantic occurred in the Caribbean Sea around 1943 (Fenner, 2001; Fenner and Banks, 2004; Creed et al., 2017). *Tubastraea* spp. successfully invaded many natural and artificial habitats, along 4000 km of coast in tropical, subtropical, and temperate waters of the SW Atlantic (Brazil) (Creed et al., 2017; Soares et al., 2018, 2020). *Tubastraea* colonies are commonly associated with coral reefs, rocky shores, mussel beds, wood debris, marine litter, and stationary artificial substrates, such as ferrous shipwrecks, ports, and offshore oil and gas structures (Creed and de Paula, 2007; Mantellato and Creed, 2015; Miranda et al., 2016; Creed et al., 2017; López et al., 2020; Mantellato et al., 2020).

In the mid-1980s, both invasive species were first introduced to the Rio de Janeiro coast through biofouling associated with drillships, monobuoys, and oil and gas structures (Paula and Creed, 2004, 2005; Creed, 2006). In spite of these species formerly being present in subtropical waters of the Campos Basin oil region (Rio de Janeiro state), 22° S latitude, their distribution expanded north and southward in the following decades (Creed et al., 2017; Saá et al., 2020). In 2016 and 2020, the northernmost presence of *Tubastraea* corals was noticed at 2° S in the equatorial SW Atlantic (Creed et al., 2017; Soares et al., 2018, 2020), on the Brazilian equatorial continental shelf (BES) (Jovane et al., 2016). The BES is a low-latitude region between 6° N to 6° S in the Southwestern Atlantic, which includes the Amazon coast and the Brazilian semiarid coast (Fig. 1).

Their negative impacts on benthic and fish species, marine economy sectors (e.g., fishing and tourism), and traditional human populations have been well documented in literature (Lages et al., 2011; Luz and Kitahara, 2017; Mizrahi et al., 2017; Silva et al., 2017; Vinagre et al., 2018; Miranda et al., 2018a, 2018b, 2020). Furthermore, *Tubastraea*

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coral bioinvasion brings economic costs and uncertainties in environmental licensing of high-value sectors, such as the oil and gas industry (Petrobras, 2019, 2020).

The oil and gas industry and its exploration/production structures were suitable habitats (e.g., fixed platforms) or important vectors for *Tubastraea* spp. coral range dispersion (drillships, floating platforms, and monobuoys) in Brazil (Costa et al., 2014; Castro et al., 2017; Creed et al., 2017), the Gulf of Mexico (Fenner, 2001) and west Africa (Friedlander et al., 2014). Genetic studies showed that its dispersion success, range expansion, and invasiveness were linked to diverse vectors, asexual reproduction, competition strategies, early reproduction, high recruit numbers, heterotrophic feeding, environmental plasticity, and high degree of competition (Paula et al., 2014; Capel et al., 2017; Creed et al., 2017; Saá et al., 2020). In addition, its occurrence in a large area in the Brazilian coast was attributed to stepping stone habitats, rafting, secondary dispersion, and multiple introductions (Capel et al., 2019; Mantellato et al., 2020; Soares et al., 2020) in oil and gas production areas.

The BES region (6° N to 6° S) (Fig. 1) is a frontier between SW Atlantic and Caribbean Sea. With 36 oil and gas fields, its current production facilities are located in the states of Ceará and Rio Grande do Norte (ANP, 2020). However, since many of these oil and gas field platforms built in the 1980s are currently working at low production rates and significant economic costs, they are likely to be retired or decommissioned (e.g., rigs-to-reefs) in the upcoming years (Brasil, 2020). These oil production deactivation phases must be accompanied by rigorous environmental actions (Saisse and Messano, 2019), especially if structures are colonized by this invasive species. Moreover, there is a significant potential for industry expansion in shallow and deeper waters in these two Brazilian states and in the northernmost regions (Fig. 1), such as the Amazonian coast, due to the recent discovery of new oil and gas fields (ANP, 2020; PETROBRAS, 2020) that could threaten local marine biodiversity due to *Tubastraea* spp. expansion.

With its high production potential, BES is considered a new frontier for oil and gas exploration (PETROBRAS, 2019; ANP, 2020) (Fig. 1). However, the existence of poorly studied marine ecosystems of utmost importance, such as the marginal shallow-water reefs, mesophotic ecosystems (Soares et al., 2019) and Great Amazon Reef System (GARS) (Moura et al., 2016; Francini-Filho et al., 2018; Mahiques et al., 2019) (Fig. 1), led to recent denials of environmental licenses for oil and gas exploration in this tropical region.

The objective of this study was to report, for the first time, the presence of the invasive coral (*Tubastraea tagusensis*) in an oil platform in BES. Furthermore, we discussed the environmental risk of the presence of this coral in the region and the environmental management actions that can be urgently adopted, considering the new national regulations and good international decommissioning and retirement practices for oil and gas platforms.

The present study was conducted in BES over the continental shelf of Ceará (Fig. 2), characterized by oligotrophic waters, strong waves and winds, and mesotidal regimes, where oil and gas platforms were installed in shallow waters (<50 m) (Teixeira and Machado, 2013). The continental shelf has 3 parts: inner (<20 m), middle (20–40 m), and

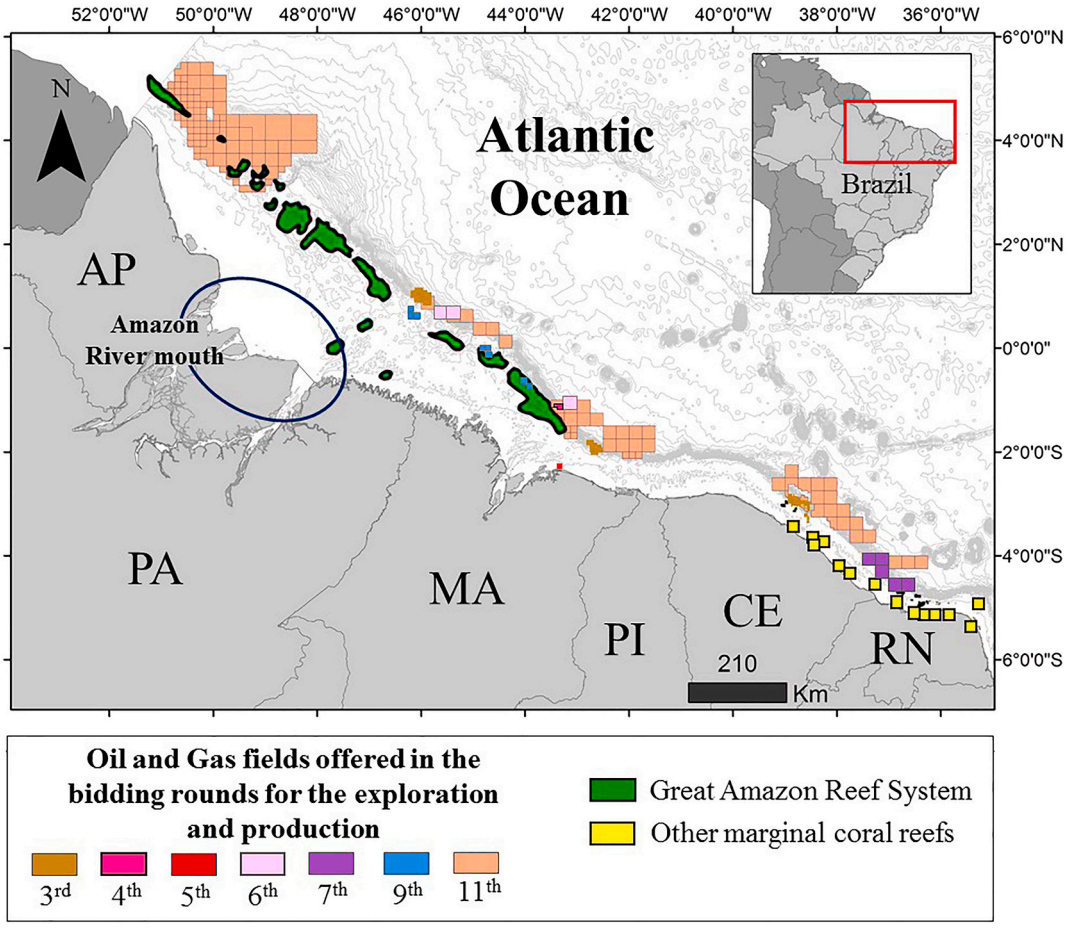

Fig. 1. Brazilian equatorial continental shelf (BES), mapped reef systems (green and yellow colors), Amazon River mouth, and new oil and gas fields offered in bidding rounds for exploration and production by national and international companies in the region. Brazilian states: AP = Amapá, PA = Pará, MA = Maranhão, PI = Piauí, CE = Ceará, and RN = Rio Grande do Norte. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

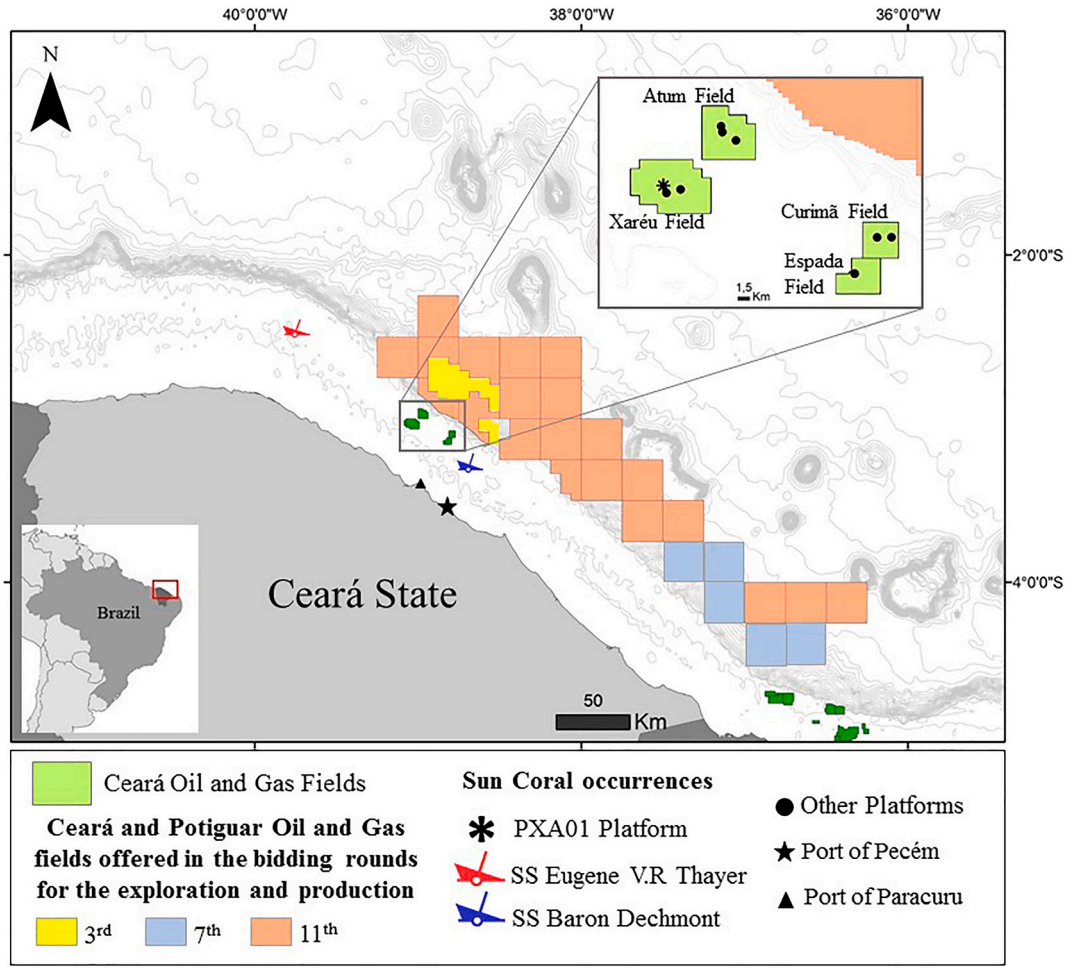

Fig. 2. Ceará state coast (Brazilian equatorial continental shelf), four oil and gas fields and their nine platforms (green color), new oil and gas fields (yellow, blue, and orange color) offered in the national bidding rounds, and shipwrecks and PXA01 (oil platform) invasive coral occurrences. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

outer portions (>40 m to the shelf break, ~60–70 m) (Morais et al., 2019). A particular feature of this region is a warm and fast-flowing (~0.15 m s^{-1} average) westward continental shelf current fed by trade winds (Teixeira and Machado, 2013; Dias et al., 2018). This continental shelf is characterized by seagrass meadows, rhodolith beds, *Halimeda* beds, submarine dunes, shallow-water turbid coral reefs and mesophotic ecosystems, and incised valleys (Soares et al., 2017, 2019; Morais et al., 2019; Costa et al., 2020). The sea surface temperature range is 26.5–30 °C with stable intra- and inter-annual variation, and small riverine freshwater input to the shelf (Teixeira and Machado, 2013; Soares et al., 2017).

Built in the early 1980s, the cluster of nine oil and gas platforms and 32 exploration wells, which comprises four fields (Atum, Curimã, Espada, and Xaréu), are located 30 km off the coast of Ceará state, between 30 and 50 m below the mean waterline (Fig. 2). In 2019, the average production in the whole area was 4.2 thousand barrels per day of oil and 76.9 thousand m^3/day of gas. Petrobras (*Petróleo Brasileiro S.A* – a publicly held company) was the field operator.

In order to identify the possible presence of *Tubastraea* corals on oil and gas platforms in BES, we searched for images and videos on several streaming platforms recorded by professional divers (possibly helmet images during underwater services in the oil platforms of Ceará basin, near Paracuru city, Brazil) (Fig. 2). High-quality recordings allowed the footage frame extraction and invasive coral identification based on the morphology and criteria (e.g., the color of coenosarc is yellow and the spacing of corallites is closely spaced, among other characters) described by Paula and Creed (2004, 2005) and Soares et al. (2018, 2020).

The presence of *Tubastraea tagusensis* was verified by citizen science approach (e.g., videos and photographs produced by divers), which was widely used due to low cost and use of Information and Communication Technologies (Johnson et al., 2020); it was considered a relevant source of data regarding human activities affecting natural organisms (Toivonen et al., 2019; Giglio et al., 2020). Information regarding current and projected oil and gas platforms in BES (Figs. 1 and 2) was obtained from the National Agency for Petroleum, Natural Gas and Biofuels (ANP, 2020). The spatial data of oil and gas platforms, reefs, and isobaths from the nautical charts were processed using QGIS software to generate the maps of potential areas for *Tubastraea* coral dispersal (Figs. 1, 2, and 4).

Morphological analyses based on the two videos from 2015 and 2018 indicated the presence of *Tubastraea tagusensis* on a fixed oil platform in BES (Fig. 3). Despite the existence of nine oil and gas platforms in the Ceará basin, we can only confirm the presence of *T. tagusensis* in one oil platform from Xaréu field (PXA-1), since the name of the oil platform and field (Fig. 1) was described in the title of the video. Nevertheless, a careful analysis of all platforms (Fig. 2) was fundamental to investigate the hypothesis of spread of invasive corals within in the cluster of four exploration fields, due to the geographical proximity between structures (<20 km), environmental conditions (Carlos-Júnior et al., 2015), and short-term natural dispersion by coral larvae (or groups of polyps) (Jokiel, 1990; Mizrahi et al., 2014; Paula et al., 2014; Barbosa et al., 2019), rafting (wood debris and marine litter) (Mantellato et al., 2020) or associated vessels (Creed et al., 2017; Soares et al., 2020). Data from

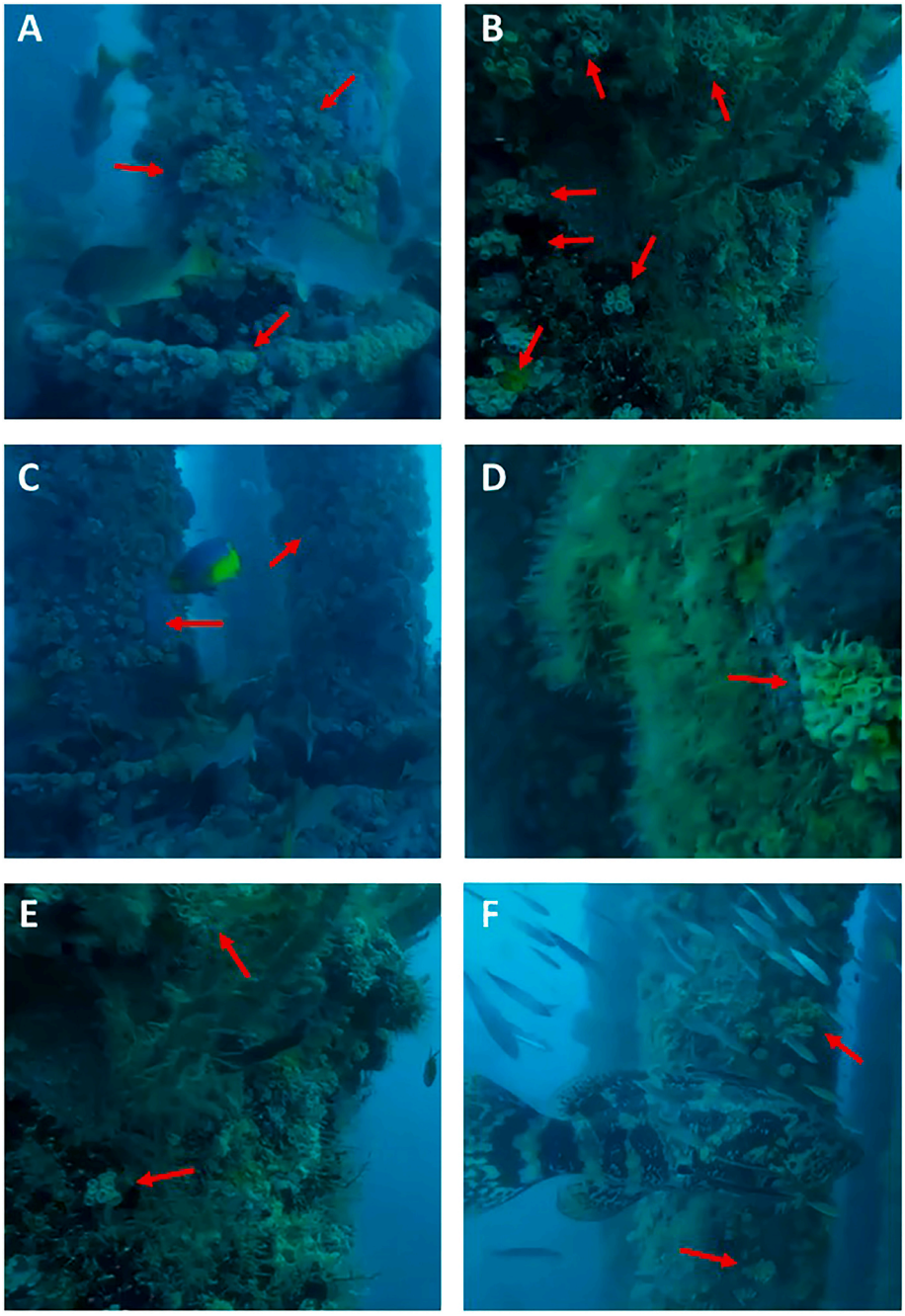

Fig. 3. *Tubastraea tagusensis* colonies (red arrows) recorded at 10 m depth on an oil platform (PXA-1 platform, Ceará coast, Brazilian equatorial continental shelf) in 2015. A, B, C, D, E, and F: *Tubastraea tagusensis* and associated fauna, including fishes (*Holacanthus ciliaris* and *Epinephelus itajara*) and benthic invertebrates, such as sponges and bryozoans. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the other platforms in further studies would be necessary to determine whether they had spread (or not).

The PXA-1 platform (Fig. 2) where the invasive coral was found (Fig. 3) began oil production in 1981 (ANP, 2016), having been built/refurbished probably on the coast of Bahia (where invasive species also occurs) (Creed et al., 2017) and transported to the coast of Ceará (~1500 km distant). In a similar context in the southwest Atlantic, Creed et al. (2017) argued that the *Tubastraea* spp. were introduced in Rio de Janeiro in the 1980s through biofouling on oil platforms and/or drill ships, probably redeployed from Africa, the Gulf of Mexico or Indo-Pacific via the Straits of Magellan or the Cape of Good Hope. Such statement is corroborated by the fact that these invasive corals are sensitive to rapid water movement associated with modern ships and boats and are generally absent when compared to other fouling organisms. On the other hand, *Tubastraea* spp. have been observed to survive well on slow moving drill ships and objects, such as the oil platforms P-27 and P-14, which were towed 1280 and 1440 km, respectively, to port where they remained living and subsequently reproductive (Creed et al., 2017). Thus, the hypothesis that this invasion is old and resulted from transportation through biofouling on oil platforms, monobuoys, and/or drill ships could be also valid. However, this hypothesis needs further investigation using genetic analysis (e.g., microsatellite markers), studies of population structure (e.g., to estimate size and age), and old videos from previous decades to be confirmed (Capel et al., 2019; Soares et al., 2020).

The video used to identify *Tubastraea tagusensis* on PXA-1 was

published in July 2015 (Fig. 3), one year before its first official registration by the academic community in a shipwreck (SS Eugene V.R Thayer) on the Ceará coast (Soares et al., 2018). In marine environments, submerged oil production structures must be constantly inspected and cleaned due to the deteriorating action of biofouling; a rigorous environmental monitoring project is needed for early detection of invasive marine species. Therefore, if this video had been carefully watched by either industry managers or environmental monitoring teams, they could be aware of the presence of *T. tagusensis* in this oil field, and cleaning and monitoring activities could have already been initiated (Bull and Love, 2019).

In 2020, a record of invasive coral was found in a WWII shipwreck SS Baron Dechmont (Soares et al., 2020). Since the present register was recorded prior to shipwreck, it is possible that the oil and gas platforms are its source, so genetic analysis and verification of old videos from previous decades must be conducted, as approached by Capel et al. (2019) and Soares et al. (2020). The population of *T. tagusensis* found in a WWII shipwreck SS Eugene Thayer in BES was genetically distinct from other populations (Soares et al., 2018; Capel et al., 2019), since the northernmost specimens do not share multi-locus genotypes with any other individuals or vectors in the rest of Brazil; therefore, it is the most divergent population (Capel et al., 2019). This suggests that BES was colonized by a distinct source population, not present in sites or vectors analyzed in Brazil, and was probably the result of a single introduction event (Capel et al., 2019), followed by secondary dispersions between oil and gas platforms, and shipwrecks (Soares et al., 2020).

Recently, *Tubastraea coccinea* was also detected on both shipwrecks (SS Eugene Thayer and SS Baron Dechmont) (Fig. 2). In this way, DNA analysis may reveal further that *T. tagusensis* and *T. coccinea* occur together in oil and gas platforms in this region (Paula and Creed, 2004; Creed and de Paula, 2007; Soares et al., 2018; Soares et al., 2020). Unfortunately, to date, this hypothesis concerning *Tubastraea* spp. bioinvasion in BES remains unclear as invasive corals were found exclusively in two WWII shipwrecks and PXA-1 platform.

The northernmost oil production structure colonized by this coral was located more than 1200 km away from the nearest oil and gas structures in NE (Sergipe state) and SE (Espírito Santo state) Brazil (Costa et al., 2014; Creed et al., 2017). Considering that the invasive coral is commonly associated with oil and gas exploration and transportation, and increasing interest to explore these energy matrices in poorly known vulnerable marine ecosystems, the installation of new oil and gas facilities in BES (Figs. 1 and 2) should be avoided until careful risk analysis assessments, detailed environmental characterization, high-resolution mapping of the continental shelf, and potential bioinvasion impacts are rigorously evaluated.

Such preventive measures are imperative because the azooxanthellate invasive coral has the potential to invade the Great Amazon Reef System, and to be either naturally (e.g., polyps or larvae) (Mizrahi et al., 2014; Barbosa et al., 2019) or artificially transported through the marine debris (Mantellato et al., 2020) and intense vessel flow integrating the BES, Gulf of Mexico, and Caribbean coral reefs (Sammarco et al., 2013, 2015). The BES presents strong (average 0.15 m s^{-1}) subtidal currents that can lead to a westward larval advection close to 200 km in 15 days. New and old oil and gas platforms can be the artificial stepping stone habitats, facilitating the dispersion and range expansion of *Tubastraea* spp. and other invasive species (Saura et al., 2014). This process was recently recognized for old and recent shipwrecks, which led to criticism of the Brazilian Federal Government's unplanned project

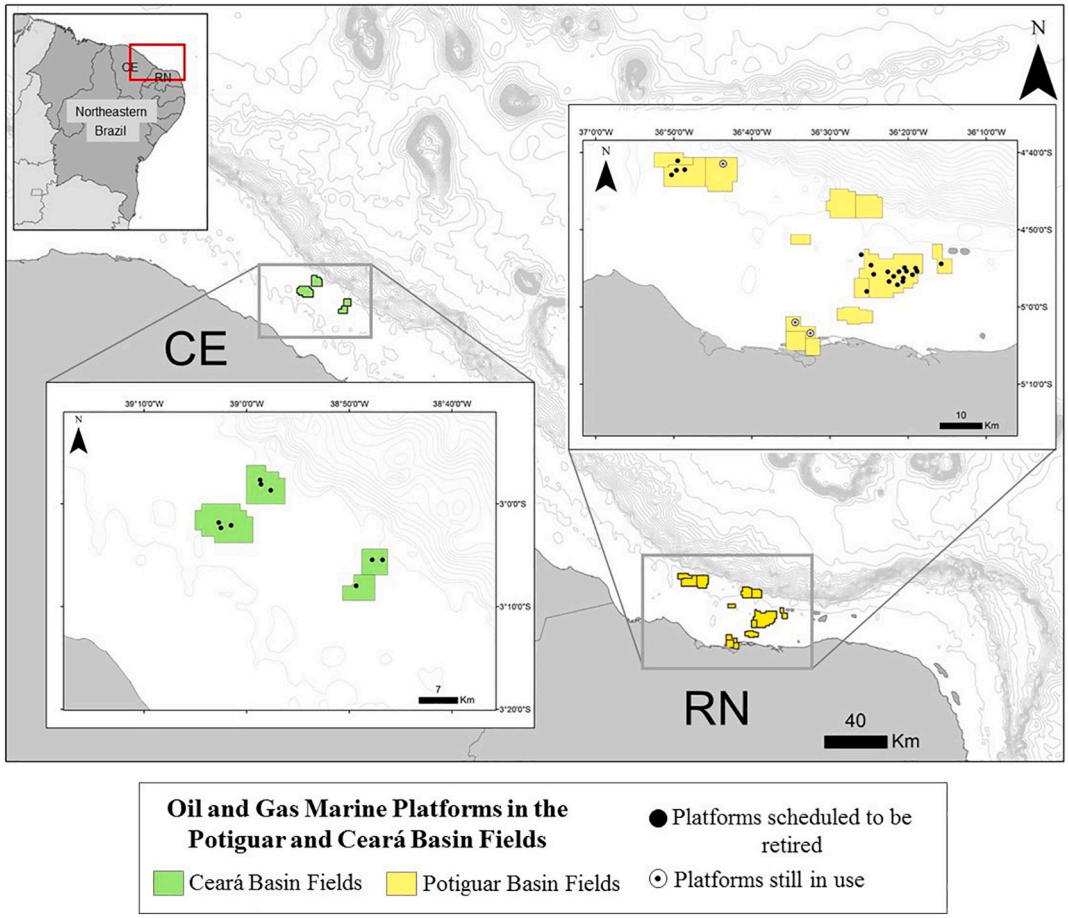

Fig. 4. Ceará and Rio Grande do Norte state coasts on the Brazilian equatorial continental shelf (BES), showing some of the oil and gas field platforms scheduled to be retired.

to install new artificial reefs to promote scuba diving near marine protected areas and coral reefs (Miranda et al., 2020; Soares et al., 2020).

Another aspect that deserves special attention is the decommissioning of biofouling-encrusted oil and gas platforms (Fig. 4) as a result of the current oil crisis, exacerbated by the COVID-19 pandemic. Brazil is expected to face a great decommissioning movement in the upcoming years after a series of disinvestment measures by the Brazilian Petroleum Corporation-Petrobras, which announced the retiring of 62 oil and gas platforms (Petrobras, 2019), and as the only operator of the Ceará basin started the opportunity disclosure stage referring to the sale of the entire stake in Atum, Curimã, Espada, and Xaréu fields (Petrobras, 2020).

This sale is aligned with the strategy of optimizing the portfolio and improving the allocation of the company's capital, focusing its resources on deep and ultra-deep waters (e.g., pre-salt exploration), where Petrobras has demonstrated great competitive differential over the years (ANP, 2020). Due to high maintenance costs of old structures associated with decreasing production over the decades (25,000–30,000 bbl/day in the mid-1980s compared to c. 5000 bbl/d in the beginning of 2020, before retirements) (ANP, 2020), Ceará state oil and gas platforms support this possibility for future decommissioning (Fig. 4) or giveaway rights decisions; hence, the most appropriate disposal of biofouled retired structures presents a real challenge.

Oil platform decommissioning in Brazil is currently regulated by an administrative norm, Resolução ANP 817/2020 (Brasil, 2020), issued by the Brazilian National Agency of Petroleum, Natural Gas, and Biofuels (*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis-ANP*), in collaboration with the Brazilian Navy (*Marinha do Brasil*) and Brazilian Institute of the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA). According to this norm, an installation decommissioning program (*Programa de Descomissionamento de Instalações* – PDI) with alternative proposals accomplishing multicriteria analysis approaches (e.g., technical, environmental, social, security, and economic aspects) must be presented whenever an oil (or gas) platform will be decommissioned. IBAMA is responsible for analyzing environment-related issues, in which environmental restoration and non-indigenous species dispersal, and more specifically *Tubastraea* coral bioinvasion, have been subjects of major concern.

To identify and prevent the bioinvasion of *Tubastraea* spp. and other non-indigenous species, and to assist in decision-making processes, IBAMA requires oil and gas companies to present risk analysis studies as part of the different phases of environmental licensing process (Saisse and Messano, 2019). In addition, IBAMA is currently elaborating an administrative norm (*Instrução Normativa* – administrative process SEI 02022.000244/2016-35) for the inspection and eradication of biofouling from submerged artificial substrates. Such initiatives are particularly important when complete removal of retired oil and gas platforms from the seafloor is not considered the best decommissioning alternative, and artificial reefing (rig-to-reef) is the selected option. Since the steel fixed platforms are in shallow waters of Ceará state, decommissioning through the complete removal of the structures is feasible (Figs. 2 and 4). However, if these platforms are sold and have their production life extended, or are converted into artificial reefs by tow-and-place, topplein-place, or partial removal platform reefing (Bull and Love, 2019), manual collection of *Tubastraea* spp. by divers seems to be the best alternative to control or eradicate local populations of invasive corals, avoiding their dispersal into natural ecosystems (Figs. 2 and 4).

In conclusion, the first record of *Tubastraea tagusensis* on a fixed oil platform in Brazilian equatorial coast and the appropriate disposal of biofouled structures present real challenges. Moreover, this record highlights a concern due to the potential range expansion to other Brazilian regions, Gulf of Mexico, Macaronesia, and Caribbean Sea through stepping stone habitats and oil and gas industry. The unprecedented impacts that may be caused by coral invasion into scarcely studied and vulnerable marine ecosystems, such as shallow-water marginal coral reefs and mesophotic ecosystems in the equatorial SW Atlantic (e.g., Amazon Reefs) warn that the installation of new oil and gas platforms must be avoided until risk analysis assessments and rigorous environmental studies (e.g., genetic analyses of invasive species, high-resolution mapping of the seafloor and their benthic ecosystems, and vector analysis). In addition, decommissioning of biofouling-encrusted platforms should follow environmentally friendly protocols (e.g., rigs-to-reefs must be avoided), and analyze marine restoration, structure transportation, and non-indigenous species dispersion, specifically *Tubastraea* coral bioinvasion.

CRediT authorship contribution statement

Marcus Davis Andrade Braga: Conceptualization, Writing – original draft, Writing – review & editing, Methodology, Formal analysis. **Sandra Vieira Paiva:** Conceptualization, Writing – original draft, Writing – review & editing, Methodology, Formal analysis. **Lívio Moreira de Gurjão:** Writing – original draft, Writing – review & editing, Formal analysis. **Carlos Eduardo Peres Teixeira:** Writing – original draft, Writing – review & editing, Formal analysis. **Anne Larisse Gurgel:** Writing – original draft, Writing – review & editing, Formal analysis. **Pedro Henrique Cipresso Pereira:** Writing – original draft, Writing – review & editing, Formal analysis. **Marcelo de Oliveira Soares:** Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Methodology, Supervision.

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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