

UNIVERSIDADE FEDERAL DE SANTA CATARINA
CURSO DE GRADUAÇÃO EM OCEANOGRAFIA

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**VARIABILIDADE ESPAÇO-TEMPORAL DA COMUNIDADE BENTÔNICA
RECIFAL DO ARQUIPÉLAGO DE FERNANDO DE NORONHA, PE**

Trabalho de Conclusão de Curso apresentado ao curso de Graduação em Oceanografia da Universidade Federal de Santa Catarina como parte dos requisitos necessários para obtenção do Título de Bacharela em Oceanografia.

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Trabalho de Conclusão de Curso julgado adequado para a obtenção do Título de “Bacharela em Oceanografia” e aprovado em sua forma final pelo Programa do Curso de Graduação em Oceanografia.

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*“ Dias inteiros de calma,
noites de ardência,*

*dedos no leme e
olhos no horizonte,*

*descobri a alegria de transformar
distância em tempo.*

Um tempo em que aprendi

*a entender as coisas do mar,
a conversar com as grandes ondas
e não discutir com o mal tempo.*

*A transformar o medo em respeito,
o respeito em confiança.*

*Descobri como é bom chegar
quando se tem paciência.*

*E para se chegar onde quer que seja,
aprendi que não é preciso dominar a força,
mas a razão.*

*É preciso antes de mais nada
querer. “*

- Amyr Klink

RESUMO

Ambientes recifais são um dos mais ricos ecossistemas marinhos, constituindo importantes ambientes de produção primária em águas rasas tropicais e subtropicais e fornecendo habitat e alimentação para diversas espécies marinhas. Todavia, a intensa ocupação da zona costeira tem levado à degradação desses ambientes, com consequentes perdas significativas de biodiversidade. Tais distúrbios antrópicos são ainda agravados por mudanças e eventos climáticos como o El-Niño, por exemplo, uma vez que tornam os ecossistemas ainda mais vulneráveis e menos resilientes a alterações de temperatura e pH da água do mar, por exemplo. Nesse contexto, as ilhas oceânicas têm se apresentado como importantes ambientes para o estudo da saúde ecossistêmica de ambientes recifais. Ainda que estejam suscetíveis aos impactos globais, devido ao seu isolamento geográfico as ilhas oceânicas apresentam muito menos impacto antrópico local, podendo apresentar características mais próximas de pristinas e sem o efeito sinérgico de diferentes fatores de estresse. Dessa forma, o monitoramento a longo prazo em ilhas oceânicas torna-se importante ferramenta para compreensão de variações naturais nas comunidades recifais e de possíveis efeitos de estressores isolados. Apesar de importantes, estudos de longa duração da comunidade bentônica recifal não foram realizados em ilhas oceânicas brasileiras até o momento, havendo apenas caracterizações espaciais ou análises temporais de curto prazo (sazonais e interanuais). Assim, o presente estudo teve como objetivo descrever a comunidade bentônica recifal do Arquipélago de Fernando de Noronha e avaliar a sua dinâmica espaço-temporal entre os anos de 2013 e 2016. Três sítios foram amostrados ao longo de duas faixas de profundidade, com três transectos em cada faixa e sendo amostrados 11 fotoquadrados em cada transecto. As imagens obtidas foram processadas por meio do *software* CPCe e os organismos identificados foram agrupados em grupos morfofuncionais. Dados de temperatura da superfície do mar provenientes da base de dados da NOAA também foram utilizados para caracterizar a região. Nossos resultados indicaram que, em geral, a comunidade bentônica recifal do Arquipélago de Fernando de Noronha é composta predominantemente por *turf* e macroalgas (*Sargassum* spp., *Dictyota* spp., *Dictyopteris* spp., *Amphiroa* sp. e/ou *Jania* sp.). Porém, houve diferença significativa entre as comunidades dos diferentes sítios, em especial na composição do grupo de macroalgas, o que está provavelmente relacionado à diferença de exposição à ação de ventos e ondas. Nossos resultados também indicaram mudanças significativas na comunidade do arquipélago ao longo do período de amostragem, com *turf* e macroalgas apresentando cobertura similar em 2013 e 2016 (coberturas entre 40% e 50%), porém com redução de macroalgas e aumento na cobertura de *turf* para mais

de 60% em 2014 e 2015. 2016 foi o ano mais distinto, com elevada cobertura de algas calcárias articuladas. Tais variações podem estar relacionadas a diferenças de precipitação e aporte terrígeno entre 2013 e 2014 e à possível influência do El Niño 2015/2016. A continuação desse estudo, por meio do monitoramento ao longo dos próximos anos e análise da influência de parâmetros oceanográficos na estrutura da comunidade, faz-se necessária para avaliar possíveis mudanças de fase na comunidade e a capacidade de resiliência do ecossistema.

Palavras-chave: ilhas oceânicas, macroalgas, turf, monitoramento, El Niño, Atlântico Sul Tropical

ABSTRACT

Reef environments are one of the richest marine ecosystems, representing an important primary production environment in tropical and subtropical shallow waters and supporting a variety of marine species that utilize this environment as habitat for feeding and protection. However, the intensive human occupation of the coastal zone has damaged these environments, with consequent loss of biodiversity. Anthropogenic impacts are further aggravated by climate change and events such as El-Niño, since they make these ecosystems even more vulnerable and less resilient to changes in ocean temperature and pH, for example. In this context, oceanic islands have become important environments in terms of studies about the health and biodiversity of reef ecosystems. Even though oceanic islands are affected by global climate change, owing to their geographical isolation they undergo less synergistic effect of a range of stress factors and might present features closer to pristine. In view of this context, long-term monitoring at oceanic islands are becoming an important tool in terms of understanding natural fluctuations on reef communities and the possible effect of particular stressors. In spite of their importance, long term studies about reef benthic communities of Brazilian oceanic islands have not been done yet. To date, only spatial characterization or short-term assessment (seasonal and interannual) of these communities have been described. Therefore, the present study expands the description of the reef benthic community of Fernando de Noronha Archipelago to a spatio-temporal analysis, assessing the substrate cover dynamics of three sites from 2013 to 2016. Each site was sampled at two depth ranges, with three transects at each range and 11 photoquadrats in each transect. Image processing was made by using CPCe software and the identified organisms were grouped into functional groups. Sea surface temperature data from NOAA database was also gathered in order to characterize the archipelago region. Our results showed that, overall, reef benthic community of Fernando de Noronha Archipelago is composed mostly by algal turf and macroalgae (*Sargassum* spp., *Dictyota* spp., *Dictyopteris* spp., *Amphiroa* sp. and/or *Jania* sp.). However, there was significant difference between communities from different sites, especially in terms of macroalgae category composition, probably related to differences in exposure to wind and wave action. Our results also showed significant changes in the overall archipelago community over the sampling period, with similar algal turf and macroalgal covers in 2013 and 2016 (covers between 40% and 50%), however with decrease of macroalgae and increase in algal turf (cover greater than 60%) in 2014 and 2015. 2016 stood out among other years, with high cover of articulated calcareous algae. These variations might be related to differences on precipitation and drainage between 2013 and 2014

and to the El-Niño event in 2015/2016. The continuation of this study through monitoring over the following years and analysis of the influence of oceanographic parameters on reef community structure is needed to assess possible phase-shifts and the resilience capacity of this ecosystem.

Key words: oceanic island, macroalgae, algal turf, monitoring, El Niño, Tropical South Atlantic

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INTRODUÇÃO GERAL

Ilhas oceânicas podem ser definidas como ilhas formadas pela emersão de montes submarinos conectados ao assoalho oceânico, diferenciando-se de ilhas continentais por nunca terem sido conectadas a nenhum continente (THORNTON, 2007). Segundo Almeida (2006), a origem de ilhas oceânicas está fortemente relacionada à deriva continental e tectônica de placas, sendo resultado da passagem de uma fratura da placa por um *hotspot* com conseqüente formação de um vulcão submarino que, se emerso, apresenta-se como ilha.

Ilhas oceânicas são ambientes de grande importância no estudo de biodiversidade e conservação de ecossistemas, tendo em vista suas características peculiares resultantes do isolamento geográfico. A distância da zona costeira e até mesmo a presença de plataformas íngremes ao seu redor, por exemplo, fazem das ilhas oceânicas ambientes isolados, com altas taxas de endemismo (FLOETER et al., 2008) e, muitas vezes, *hotspots* de biodiversidade, no caso de ilhas maiores e mais isoladas (VERMEIJ, 2004). Segundo Hachich et al. (2015), tais características são altamente dependentes da área, idade e isolamento da ilha, fatores que influenciam o nível de fluxo genético e o assentamento de espécies na região.

Com cerca de 8000km de costa, o Brasil possui quatro ilhas e arquipélagos oceânicos: na região equatorial, Arquipélago de São Pedro e São Paulo (0°55'N; 29°21'O), Arquipélago de Fernando de Noronha (3°54'S; 32°25'O) e Atol das Rocas (3°50'S; 33°49'O); na região tropical, complexo insular de Trindade (20°30'S; 29°20'O) e Martin Vaz (20°30'S; 28°52'O) (ALMEIDA, 2006). Dada essa grande extensão latitudinal, o país apresenta tanto recifes biogênicos quanto recifes rochosos ao longo de seu litoral, sendo os primeiros encontrados especialmente no litoral nordeste (MAIDA; FERREIRA, 1997) e os segundos preferencialmente nos litorais sudeste e sul (FLOETER et al., 2001). Segundo Floeter et al. (2008), as ilhas oceânicas brasileiras pertencentes a um mesmo arquipélago apresentam uma forte conectividade entre seus recifes e um grande percentual de endemismo, muitas vezes peculiar ao arquipélago e diferente dos demais, de modo que cada arquipélago brasileiro possa ser estudado como uma unidade biogeográfica.

É importante destacar que, em função do isolamento geográfico, o comportamento climático e oceanográfico em ilhas é diferente quando comparado à zona costeira, o que também pode influenciar a composição biológica local. A presença de plataformas íngremes e profundas ao redor das ilhas, por exemplo, com menor impacto de ondas, facilita o assentamento de algumas espécies de corais (STORLAZZI et al., 2002). Krajewski e Floeter (2011), por exemplo, detectaram a maior cobertura coralínea do Arquipélago de Fernando de

Noronha (20%) entre 12 e 18 metros de profundidade, a qual, segundo os autores, também leva à elevada densidade e biomassa de peixes nessas regiões.

Ao redor das ilhas também há presença de correntes oceânicas diferenciadas em relação à costa, as quais exercem grande influência na circulação de organismos e fluxo genético e, conseqüentemente, na biodiversidade local. Segundo Hachich et al. (2015), devido à profundidade ao seu redor, ilhas e arquipélagos oceânicos são também menos influenciados por mudanças no nível do mar do que a região costeira, quando se trata da conectividade com regiões fontes de espécies.

Por fim, devido à menor presença de rios, ilhas oceânicas apresentam menor aporte sedimentar e de água doce, característica bem diferente da zona costeira. Águas com menor turbidez, temperaturas mais baixas e maior salinidade compõem ambientes propícios ao estabelecimento de corais (ESTADOS UNIDOS, 2014).

Impacto antrópico em ambientes costeiros e insulares

O rápido crescimento populacional e a constante necessidade por recursos energéticos e alimentícios têm gerado uma crescente busca por espaço e fontes capazes de suprir essa demanda. Em função da versatilidade da zona costeira para o desenvolvimento de diversas atividades, como turismo, pesca e atividade portuária, aliada ao desejo de viver próximo ao mar, uma parcela significativa da população mundial passou a se estabelecer nessa região ao longo do tempo. Segundo Hinrichsen (1999), já em 1998 mais da metade da população mundial vivia a menos de 200km da costa e dois terços viviam a menos de 400km.

Além da intensa ocupação, a qual leva à modificação de habitats, sedimentação e poluição, a crescente demanda por energia e alimento leva à exploração desenfreada de recursos, ocasionando degradação de ecossistemas e perdas significativas de biodiversidade (HALPERN et al., 2015). Segundo Washington (1995), em 1995 metade dos ecossistemas costeiros do mundo já sofriam o impacto do desenvolvimento urbano e da exploração de recursos. Tais distúrbios antropogênicos têm sido ainda fortemente agravados pelas mudanças climáticas, uma vez que tornam os ecossistemas ainda mais vulneráveis e menos resilientes a alterações de temperatura e pH da água do mar, por exemplo (PRATCHETT et al., 2008). A El-Niño Southern Oscillation (ENSO) é um exemplo de evento climático que causa anomalias na temperatura da superfície do mar e pode levar a eventos de branqueamento em corais e mudanças de fase em comunidades recifais em todo o planeta, inclusive no Brasil (HUGHES et al., 2003; LEÃO; KIKUCHI; OLIVEIRA, 2008; FERREIRA et al., 2006; FERREIRA et al.,

2013). O ENSO 2015/2016, por exemplo, foi especialmente forte e impactou negativamente recifes de todo o mundo (HUGHES et al., 2017).

Devido ao esgotamento de fontes tradicionais de recursos – pesqueiros, por exemplo –, a busca por novas fontes tem crescido e expandido, atingindo inclusive ambientes insulares isolados. O próprio turismo tem levado à crescente ocupação humana dessas regiões, com consequentes problemas de poluição. Recifes de corais tem recebido especial atenção nesse contexto em função da sua importância como ecossistemas chave, suportando uma extensa e complexa cadeia trófica e fornecendo diversos serviços ecossistêmicos aos seres humanos. É importante ressaltar a dependência humana desses serviços e do bom funcionamento dos processos ecológicos (BARNOSKY et al., 2012) e como os próprios seres humanos são impactados por seu uso irresponsável.

Efeitos da pressão deletéria da urbanização em ambientes recifais brasileiros já tem sido registrados há algum tempo (e.g. MAIDA; FERREIRA; BELLINI, 1995; LEÃO; KIKUCHI, 2005) e, apesar de algumas ilhas oceânicas estarem sob certo grau de proteção legal por meio do Sistema Nacional de Unidades de Conservação (SNUC), esses ecossistemas não estão totalmente protegidos. Ilhas como Fernando de Noronha, ainda que de forma controlada, recebem milhares de turistas anualmente, o que pode impactar os ecossistemas recifais seja por degradação física durante mergulhos, por poluição ou pela própria infraestrutura necessária para o turismo na região (LEÃO; KIKUCHI, 2005).

Halpern et al. (2008) estudaram o nível de impacto de diferentes fatores antrópicos (agrupados em mudanças climáticas, pesca e poluição) sobre ecossistemas marinhos ao redor do mundo, classificando-os de 0.01 a 90.1. Segundo o autor, a região das ilhas oceânicas brasileiras está inserida em uma área predominantemente de médio impacto (4.95 a 8.47). Mudanças climáticas e pesca apresentaram os maiores índices de impacto.

Monitoramento a longo prazo em ilhas oceânicas

Em um contexto de intensa degradação de ecossistemas costeiros e marinhos e de mudanças climáticas cada vez mais fortes, as ilhas oceânicas têm se apresentado como importantes ambientes para o estudo da saúde ecossistêmica de ambientes recifais. Ainda que estejam suscetíveis aos mesmos impactos climáticos globais que a zona costeira e que sofram alguns impactos relacionados a pesca e poluição, devido ao seu isolamento geográfico as ilhas oceânicas não apresentam o efeito sinérgico de diferentes fatores de estresse (SANDIN et al., 2008). Segundo Friedlander e DeMartini (2002), algumas ilhas oceânicas podem até mesmo

constituir refúgios aos distúrbios antropogênicos, apresentando características quase pristinas em seus ecossistemas.

Dessa forma, monitoramento a longo prazo de ecossistemas em ilhas oceânicas torna-se uma importante ferramenta para a compreensão de variações naturais em ecossistemas recifais insulares, obtendo informações sobre as condições naturais do ambiente e sobre como fatores isolados, como pesca, poluição e mudanças climáticas têm sido responsáveis por alterações nas comunidades recifais (SANDIN et al., 2008). Com base nessas informações é possível também avaliar o grau de degradação dos ambientes recifais costeiros e estruturar planos de manejo para reduzir o impacto e/ou melhorar a resiliência do ambiente para futuros impactos (FLOWER et al., 2017). Segundo Hughes et al. (2003), ainda que mudanças climáticas sejam um problema global, esforços locais de conservação são importantes para manter a resiliência e evitar danos a longo-prazo.

Dentre os projetos existentes no Brasil está o Monitoramento de Longa Duração das Comunidades Recifais das Ilhas Oceânicas Brasileiras (ILOC), proposta inserida na chamada de Pesquisa Ecológica de Longa Duração (PELD) do Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). O projeto envolve pesquisadores das Universidades Federais do Ceará, Espírito Santo, Rio de Janeiro e Santa Catarina e tem como objetivo monitorar os ecossistemas recifais das ilhas oceânicas brasileiras - Arquipélago de São Pedro e São Paulo, Arquipélago de Fernando de Noronha, Atol das Rocas e Ilha da Trindade - como um todo, desde componentes bióticos, como plâncton, nécton e bentos, indicadores da diversidade e saúde genética e funcional, até fatores oceanográficos, como temperatura e salinidade. Tal monitoramento é um trabalho de longo prazo para avaliar a condição e resposta das comunidades recifais das ilhas perante impactos antropogênicos, como pesca e poluição, e mudanças climáticas (FERREIRA, 2012).

Apesar de importantes, estudos de longa duração da comunidade bentônica recifal não foram realizados em ilhas oceânicas brasileiras até o momento, havendo apenas caracterizações espaciais ou análises temporais de curto prazo (sazonais e interanuais) (e.g. LABOREL, 1970; ESTON et al., 1986; PIRES et al., 1992; MAIDA; FERREIRA; BELLINI, 1995; FERREIRA et al., 2006; KRAJEWSKI et al., 2010; KRAJEWSKI; FLOETER, 2011; PEREIRA-FILHO et al., 2011; AMADO-FILHO et al., 2012; FERREIRA et al., 2013; MATHEUS, 2013; LONGO et al., 2015; MAGALHÃES et al., 2015; MEIRELLES et al., 2015; SILVA, 2016). Como parte colaboradora do projeto PELD-ILOC, o presente estudo visa dar início ao preenchimento dessa lacuna, descrevendo a comunidade bentônica recifal de três sítios do Arquipélago de Fernando de Noronha (Cagarras, Laje Dois Irmãos e Ponta da Sapata) e avaliando a dinâmica espaço-

temporal de cobertura do substrato entre os anos de 2013 e 2016. A continuação desse estudo, por meio do monitoramento ao longo dos próximos anos, faz-se necessária em termos de avaliar possíveis mudanças de fase na comunidade e a capacidade de resiliência do ecossistema a estressores como pesca, poluição e eventos climáticos como o El-Niño.

CONTEXTUALIZAÇÃO DO LOCAL

O Arquipélago de Fernando de Noronha situa-se a 3.54°S e 32.25°O, a aproximadamente 200 milhas da costa nordeste brasileira, pertencendo ao estado de Pernambuco (ALMEIDA, 2006) (Figura 1). Localizado sobre a extremidade oriental de uma cadeia de montes vulcânicos submarinos de aproximadamente 75km de diâmetro (leste-oeste), o arquipélago repousa sobre uma plataforma insular a cerca 120m de profundidade, constituindo a única parte emersa da cadeia montanhosa, a qual conecta-se com o assoalho oceânico a 4000m de profundidade. Ele possui aproximadamente 27km², perfazendo o maior arquipélago oceânico brasileiro (ALMEIDA, 2006).



Figura 1. Localização do Arquipélago de Fernando de Noronha a nordeste da costa brasileira com a indicação dos três sítios de amostragem (Fonte: GoogleEarth).

Segundo Almeida (2006), o arquipélago é composto por uma ilha principal e outras 20 ilhas menores, compostas principalmente por rochas vulcânicas. O autor destaca que sua formação original teve grande influência das variações de nível do mar do último período glacial. Com a regressão, ventos alísios de SE foram responsáveis pela formação de campos de dunas, constituídos principalmente de carbonato de cálcio de origem biogênica, que, posteriormente, vieram a dar origem aos calcarenitos da região. Com a subida do nível do mar, tais rochas deram origem às ilhas, praias, dunas e recifes de algas calcárias hoje existentes.

O clima da região é tropical de domínio oceânico e com forte influência de ventos alísios de sudeste, principalmente de abril a novembro. Assim, a porção sudeste do arquipélago é fortemente influenciada por ventos e *swells* ao longo de todo o ano e especialmente nessa época. A porção noroeste, por outro lado, permanece protegida nesse período, com baixa exposição à ação de ondas. Fortes ventos e *swells* atingem essa região de novembro a março (LINSKER, 2003). A temperatura média é de 25°C e precipitação pluviométrica anual de 1400mm, apresentando duas estações bem definidas, um período chuvoso de março a julho e um seco de

agosto a janeiro (CASTRO, 2010). A temperatura da superfície do mar ao redor do arquipélago é em torno de 27°C e a salinidade cerca de 35.5 PSU (LINSKER, 2003), sendo também influenciada pela ação da Corrente Sul Equatorial (sentido leste-oeste) (TRAVASSOS et al., 1999).

Os recifes do Arquipélago de Fernando de Noronha são predominantemente rochosos e expostos a ação de ondas, apresentando, em geral, baixa cobertura de corais (0-5%), com exceção do costão sul da Praia do Sancho e da região da Laje Dois Irmãos, nas quais a cobertura coralínea pode chegar a 12% e 20%, respectivamente (KRAJEWSKI; FLOETER, 2011). Krajewski e Floeter (2011) relataram um aumento da cobertura de corais com a profundidade no arquipélago, com as maiores coberturas ocorrendo na faixa de 12 a 18 metros de profundidade, provavelmente devido ao menor impacto da ação de ondas.

A comunidade bentônica recifal do arquipélago é composta predominantemente por *turf* e macroalgas pardas (KRAJEWSKI; FLOETER, 2011; SILVA, 2016). Eston et al. (1986) já haviam registrado alta cobertura de macroalgas na região de infralitoral, destacando a elevada biomassa e/ou porcentagem de cobertura dos gêneros *Dictyopteris*, *Dictyota* e *Sargassum*, além de *Amphiroa fragilissima* e algas calcárias crostosas (CCA). Os autores também destacam a presença de *Montastraea cavernosa*, *Siderastrea stellata* e *Mussismillia hispida* como os únicos corais com porcentagem de cobertura significativa na região. Pires et al. (1992) registraram 22 espécies da classe Anthozoa em profundidades menores que 30 metros, sendo 4 delas da ordem Zoanthidea, porém também destacaram *Montastraea cavernosa* como espécie dominante, assim como Ferreira et al. (2006) e Krajewski e Floeter (2011). Amado-Filho et al. (2012) têm registros de extensos bancos de rodólitos ao redor de todo o arquipélago entre 10 e 100 metros de profundidade.

É importante destacar que, desde 1998, 75% do arquipélago faz parte do Parque Nacional Marinho de Fernando de Noronha, o qual restringe determinadas atividades na região, como pesca em até 50m de profundidade, por exemplo, a fim de reduzir a pressão antropogênica de pesca e retirada de corais. Todavia, o arquipélago também constitui um dos pontos turísticos mais famosos do país, recebendo cerca de 60 mil turistas por ano, além dos 2.600 habitantes, o que aumenta outros focos de pressão, como poluição e modificação do ambiente devido a instalações humanas (LINSKER, 2003). Castro (2010) também destaca problemas relacionados a eventos erosivos dado a ação eólica, ação de ondas e tempestades.

O estudo “Spatio-temporal variability of reef benthic community in Fernando de Noronha Archipelago, Brazil”, apresentado a seguir, encontra-se em capítulo único em língua inglesa formatado de acordo com as normas da revista *Coral Reefs*.

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ARTIGO

**Spatio-temporal variability of reef benthic community in Fernando de Noronha
Archipelago, Brazil**

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Spatio-temporal variability of reef benthic community in Fernando de Noronha Archipelago, Brazil

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Abstract

Oceanic islands represent an important environment for studies about the health and biodiversity of reef ecosystems. This is especially due to their geographic isolation. Although they are still affected by global climate change, they undergo less synergistic effect of a range of stress factors and might present features closer to pristine. Thus, long-term monitoring at oceanic islands represent an important tool in terms of understanding natural fluctuations on reef communities and the possible effect of particular stressors. In spite of their importance, long term studies about reef benthic communities of Brazilian oceanic islands have not been done yet. To date, only spatial characterization or short-term assessment (seasonal and interannual) of these communities have been described. Therefore, the present study expands the description of the reef benthic community of Fernando de Noronha Archipelago to a spatio-temporal analysis, assessing the substrate cover dynamics of three sites from 2013 to 2016 through photoquadrats methodology. Sea surface temperature data from NOAA database was also gathered in order to characterize the archipelago region. Our results showed that, overall, reef benthic community at the archipelago is composed mostly by algal turf and macroalgae (*Sargassum* spp., *Dictyota* spp., *Dictyopteris* spp., *Amphiroa* sp. and/or *Jania* sp.). However, there was significant difference between communities from different sites, especially in terms of macroalgae category composition. This is probably related to differences in exposure to wind and wave action. Our results also showed significant changes in the overall archipelago community over the sampling period, with similar algal turf and macroalgal cover in 2013 and 2016 (covers between 40% and 50%), however with decrease of macroalgae and increase in algal turf (cover greater than 60%) in 2014 and 2015. The year of 2016 stood out among other years, with high cover of articulated calcareous algae. These variations might be related to differences on precipitation and drainage between 2013 and 2014 and to the El-Niño event in

2015/2016. The continuation of this study through monitoring over the following years and analysis of the influence of oceanographic parameters on reef community structure is needed to assess possible phase-shifts and the resilience capacity of this ecosystem.

Key words: oceanic island, macroalgae, algal turf, monitoring, El Niño, Tropical South Atlantic

Introduction

Reef environments are one of the richest marine ecosystems worldwide, representing an important primary production environment in tropical and subtropical shallow waters and supporting a variety of marine species that utilize this environment as habitat for feeding and protection (Krishnakumar et al. 2015). However, the intensive human occupation of the coastal zone has negatively impacted on these ecosystems, which have been damaged due to sedimentation, urban and industrial pollution, tourism and resources overexploitation, with consequent loss of biodiversity (Halpern et al. 2015).

Anthropogenic impacts are aggravated by climate change, since they make these ecosystems even more vulnerable and less resilient to changes in ocean temperature and pH, for example (Pratchett et al. 2008). The El-Niño Southern Oscillation (ENSO) is an example of climate event that produces anomalies on sea surface temperature and can lead to bleaching events and phase-shifts on reef communities all around the world, including Brazil (Hughes et al. 2003; Leão, Kikuchi and Oliveira 2008; Ferreira et al. 2006; Ferreira et al. 2013). Brazilian reef environments have undergone exponential and deleterious pressure of unbridled urbanization over the past few years (Leão and Kikuchi 2005) and phenomena like the ENSO 2015/2016, which was especially strong, are very likely to intensify this damage.

In a context of high degradation of marine and coastal ecosystems and increasingly intense climate change, oceanic islands have become important environments in terms of studies about the health and biodiversity of ecosystems such as coral reefs. This is especially due to their geographical isolation, what makes them environments with much less local anthropic damage when compared to the coastal zone. Even though oceanic islands are affected by global climate change, they undergo less synergistic effect of a range of stress factors and might present features closer to pristine (Sandin et al. 2008).

In view of this context, long-term monitoring at oceanic islands are becoming an important tool in terms of understanding natural fluctuations on island reef ecosystems,

providing information about environments' healthier conditions and about how particular factors, such as fishery, pollution and climate change have been responsible for shifts on reef communities (Sandin et al. 2008). Long-term monitoring also enables the assessment of ecosystem resilience to those stressors, since it allows monitoring community phase shifts (Cruz, Kikuchi and Creed 2014). Based on this, it is also possible to assess the degradation degree of coastal reef environments and deploy management plans to mitigate impacts and improve ecosystem resilience for future impacts (Flower et al. 2017).

Studies about reef benthic community and its dynamics over time might provide relevant information about health of the reef ecosystem and about its response to different stress factors. Nevertheless, to date, only spatial characterization or short-term assessment (seasonal and interannual) of reef benthic community on Brazilian oceanic islands have been described (e.g. Laborel 1970; Eston et al. 1986; Pires et al. 1992; Maida, Ferreira and Bellini 1995; Ferreira et al. 2006; Krajewski et al. 2010; Krajewski and Floeter 2011; Pereira-Filho et al. 2011; Amado-Filho et al. 2012; Ferreira et al. 2013; Longo et al. 2015; Magalhães et al. 2015; Meirelles et al. 2015). Thus, this paper expands the description of the reef benthic community of the largest Brazilian oceanic archipelago to a spatio-temporal analysis, assessing the substrate cover dynamics between 2013 and 2016.

Methods

Study Area

Fernando de Noronha is an archipelago composed by a main island and other 20 smaller islands and located 200 miles from Brazilian northeast coast (3.54°S; 32.25°W) (Figure 1). With an area of approximately 27 km², it's the largest Brazilian oceanic archipelago regarding number of islands and is situated over a 75km-diameter and 4000m-depth submarine volcanic mountain chain, representing its only emerged part (Almeida 2006).

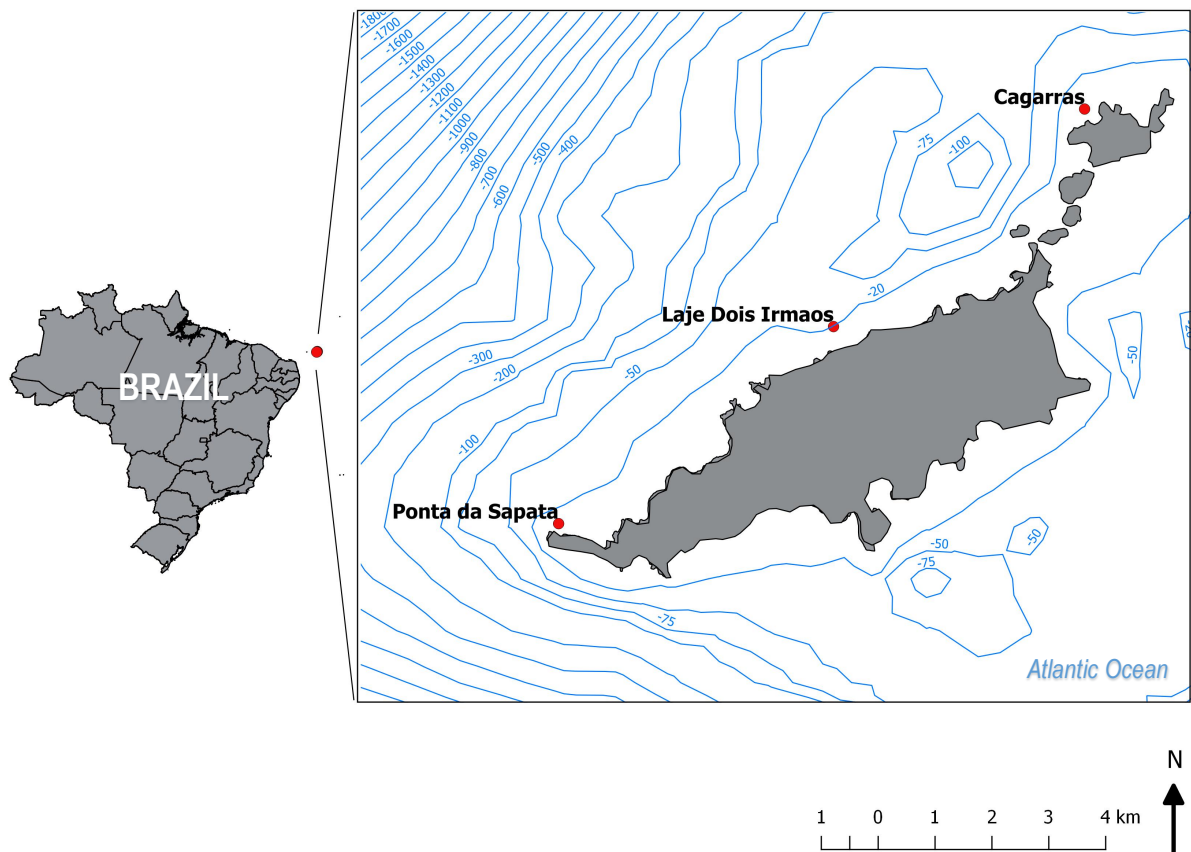


Figure 1. Location of Fernando de Noronha Archipelago at Brazil northeast coast. Sampling sites are indicated in red. Isobaths are indicated in blue. Figure made with QGIS software.

Climate at the archipelago is tropical/oceanic with strong influence of southeast trade winds, especially from April to November. Thus, the south-eastern shore faces strong winds and high swells throughout the year and stronger and higher ones during this period. The north-western shore, on the other hand, is protected from these prevailing winds, with low wave exposure from April to November and facing higher swells from November to March (Linsker 2003). Average yearly temperature is 25°C and annual rainfall is about 1400mm, with two well-defined seasons, a rainy period from March to July and a dry one from August to January (Castro 2010). Mean sea surface temperature and salinity around the archipelago are about 27°C and 35.5 PSU, respectively, being also influenced by the South Equatorial Current (Travassos et al. 1999).

Fernando de Noronha Archipelago's reefs are mostly constituted by volcanic rocks, with rocky walls that can reach from 5m to 25m deep (Krajewski and Floeter 2011). Reef benthic community is mainly composed by algal turf and brown macroalgae, especially from the genera *Dictyopteris*, *Dictyota* and *Sargassum*, besides high cover of *Amphiroa fragilissima*

and crustose coralline algae (CCA) (Eston et al. 1986). Coral cover is usually low (0-5%), except for Sancho beach southern shore and Laje Dois Irmãos, where coral cover can reach 12% and 20%, respectively (Krajewski and Floeter 2011). The most abundant corals are *Montastraea cavernosa*, *Siderastrea stellata* and *Mussismillia hispida* (Eston et al. 1986), and *Montastraea cavernosa* shows the highest cover (Pires et al. 1992; Ferreira et al. 2006; Krajewski and Floeter 2011). There are also rhodolith beds between 10m and 100m all around the archipelago (Amado-Filho et al. 2012).

Fernando de Noronha Archipelago is one of the most famous tourist spots in Brazil and, besides its 2.600 habitants, the archipelago receives 60.000 tourists per year, which creates some pressure sources, especially pollution. Since 1998 the archipelago has 75% of its area protected by the Fernando de Noronha Marine National Park, which impose restrictions to certain activities in the region, such as fishing up to 50m deep, in order to reduce anthropogenic damage (Linsker 2003).

Data Collection

To assess and describe the community structure, substrate cover data was collected through photoquadrats from three sites of Fernando de Noronha Archipelago: Cagarras (3°48'33.83"S; 32°23'23.54"W), Laje Dois Irmãos (3°50'30.25"S; 32°25'51.63"W) and Ponta da Sapata (3°52'30.65"S; 32°28'27.61"W). Samplings were performed by several researchers from 2013 to 2016, between August and October, except for Laje Dois Irmãos, where samplings have started in 2014. Cagarras and Ponta da Sapata were sampled at two depth ranges (3-5m and 9-11m, 5-7m and 10-12m, respectively) and Laje Dois Irmãos at only one (11m in 2014 and 17-21m in 2015 and 2016), due to its typical geomorphological shape. On each depth range, three transects of 20m were traced in parallel to the coastline and spaced apart by 2m. Transects were fixed with rebar to maintain the same sampling area during the different sampling years. On each transect, eleven 50x50cm photoquadrats were sampled, resulting on 1005 images (255 images per site in 2013, since photoquadrats were photographed in 4 parts, and 66 images per site in 2014, 2015 and 2016, except for Laje Dois Irmãos, which had 33 images per year).

According to Sandin et al. (2008), photograph-based analysis has been widely used on studies of reef benthic communities, especially because it is a non-destructive, relatively fast and low-cost technique, making monitoring programmes more efficient. Even though there are limitations for taxonomic identification on turbid waters, identification at functional levels and detection of changes on reef benthic communities structure are accessible, especially on clear

waters around oceanic islands, which support relatively low continental runoff (Sandin et al. 2008).

Data Processing

Data processing has consisted on image analysis in order to evaluate reef benthic community through the identification of the major functional groups on each sampling site and year. Therefore, it was used the Coral Point Count with Excel extensions (CPCe) software (Kohler and Gill 2006). Sample processing was performed by overlaying 50 random points in the image to be analysed, followed by the visual identification of the organisms below each point. To ensure standardization, all samples were processed by the same person. In this study, organisms were identified at the lower taxonomic level (usually genus) and posteriorly grouped into fine and coarse functional groups (subcategories and categories, respectively). Eight categories were defined (coral, suspension-feeder/filter-feeder, macroalgae, crustose coralline algae, turf, cyanobacteria, zoanthid and other invertebrates) and macroalgae subcategories followed functional groups established by Littler, Littler and Taylor (1983) and Steneck and Dethier (1994). Algal turf was defined based on Connell, Foster and Airoidi (2014) as low lying filamentous algae intertwined with branches of coralline algae (Table 1).

Table 1. Functional groups (categories and their respective subcategories) in which organisms were grouped in this study.

<i>Category</i>	<i>Subcategory</i>
Coral	Anthozoa
Suspension-feeder/Filter-feeder	Sponge; Ascidian
Macroalgae	Leathery; Corticated, Foliose; Filamentous; Articulated calcareous
Crustose Coralline Algae (CCA)	
Turf	
Cyanobacteria	
Zoanthid	<i>Palythoa</i> sp.
Other invertebrates	Bryozoa, Hydrozoa, Mollusca, Annelida, Crustacea and Echinodermata

Data Analyses

Relative abundance was quantified as the percent cover of each subcategory and category obtained from image analysis on CPCe. Mean values were calculated at each depth range for both subcategory and category. In order to visualize benthic community variability over the years for each site, categories were plotted for each year and site separately, indicating values for each depth range. Macroalgae subcategories were plotted separately in order to visualize spatio-temporal variations in this category composition. Categories were also plotted in terms of mean values of the three sites for each year in order to visualize benthic community temporal variability for Fernando de Noronha Archipelago as one. Plots were made by using R *ggplot2* package (Core Team R 2016).

Posteriorly, data were arcsine square-root transformed and applied to a non-metric multidimensional scaling (nMDS) with Bray-Curtis dissimilarity, in order to comprehend the community variability over the years, sites and depths (Pino 2014; Gotelli and Ellison 2011). Analysis of similarity (ANOSIM) was used to examine the significance of differences between depths, sites and years. Additionally, SIMPER analysis was made in order to identify species' contribution for those differences. Analyses were made by using PRIMER 6 β R3 (PRIMER-E 2004) software (Clarke 1993).

Temperature Data

Sea surface temperature (SST) data for Fernando de Noronha Archipelago were gathered in order to characterize the study area over the sampling period. Data were obtained from NOAA database Pathfinder Version 5.2 at Physical Oceanography Distributed Active Archive Center (PO.DAAC), which provides SST products from the Advanced Very High Resolution Radiometer (AVHRR) on a 4km global grid (Reynolds et al. 2007). Daily mean SST data from Fernando de Noronha Archipelago region (3.54°S; 32.25°W) were obtained from January to December for each of the sampled years and plotted as a time-series graph in order to visualize annual and interannual temperature fluctuations. Analyses were made by using R software (Core Team R 2016).

Results

46 taxa were identified in this study. Overall, in terms of functional groups, reef benthic community of Fernando de Noronha Archipelago was mostly characterized by algal turf and macroalgae, being consistent between sites. However, at the genus taxonomic level, there was significant differences between communities of different sites, especially in terms of macroalgae category composition. There was no significant difference between depths, though. Our results also revealed that the reef benthic community of each site has undergone temporal changes over the sampling period, especially in terms of fluctuations in covers of algal turf and macroalgae, as well as on contribution of macroalgae subcategories. Figures 2, 4 and 6 show boxplot graphs illustrating the community temporal variability in terms of percent cover of functional groups for each sampled site. In view of the structural importance of CCA and corals for the reef environment, figures 3, 5 and 7 show in more detail fluctuations in covers of these two functional groups.

Cagarras

In terms of the major functional groups, Cagarras had dominance of algal turf and macroalgae in 2013 for both depth ranges (Figure 2A), but percent cover differed between depth ranges (Table A1, Appendix S1). CCA showed the highest cover at 3-5m between all years (CCA = 7%; Figure 3A). 2014 showed an increase in algal turf cover and decrease in macroalgae, especially at 3-5m. 2014 had also higher coral cover at 3-5m (Figure 3B). Cagarras benthic community showed quite similar structure in 2015, however with greater variation of algal turf and macroalgal cover. Lastly, in 2016, algal turf and macroalgal covers were similar at both depth ranges (cover ~ 50%). This year also showed higher coral cover at 3-5m, similarly to 2014. Both CCA and corals did not show temporal fluctuations at 9-11m.

Regarding macroalgae subcategories (Figure 2B), in 2013 the community was mainly characterized by leathery algae at 3-5m (44%) and filamentous algae at 9-11m (47%). Leathery algae were absent in the following years. In 2014, macroalgal cover was dominated by filamentous algae at 3-5m (55%) and by articulated calcareous algae at 9-11m (56%). This community structure remained the same in 2015 (filamentous algae = 54% at 3-5m and articulated calcareous algae = 45% at 9-11m). Finally, in 2016, macroalgal cover was mainly characterized by foliose algae at 3-5m (53%) and filamentous algae at 9-11m (49%).

As expected, ANOSIM analysis for Cagarras indicated significant difference between years ($p=0.019$), however not between depths ($p=0.48$). 2016 was significantly different from all of the previous years and 2013 was significantly different from 2015 and 2016 ($R=1$).

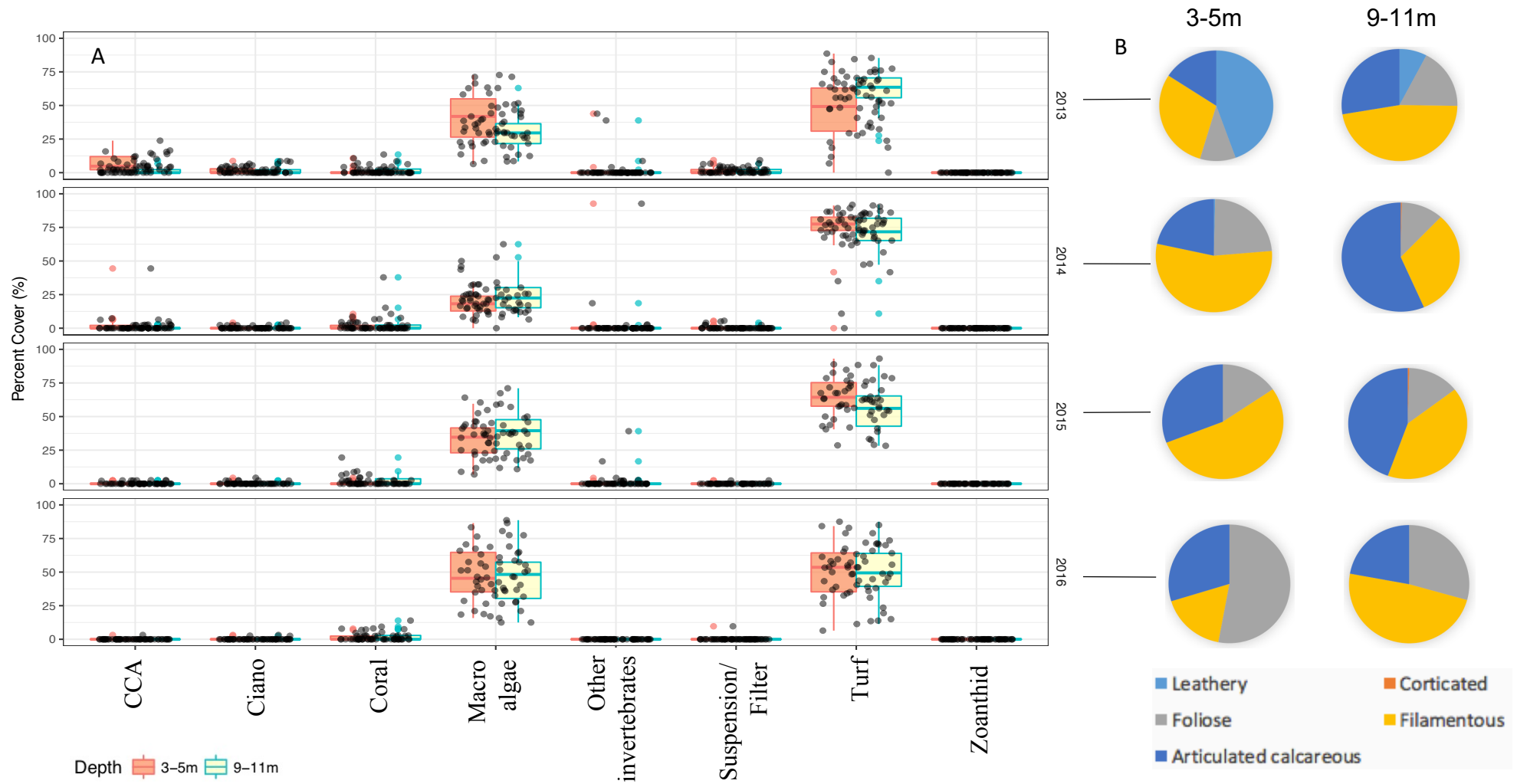


Figure 2. (A) Boxplot graphs illustrating spatio-temporal variability of reef benthic community in Cagarras. Dots represent photoquadrats distribution. **(B)** Graphs illustrating macroalgae category composition per depth and year.

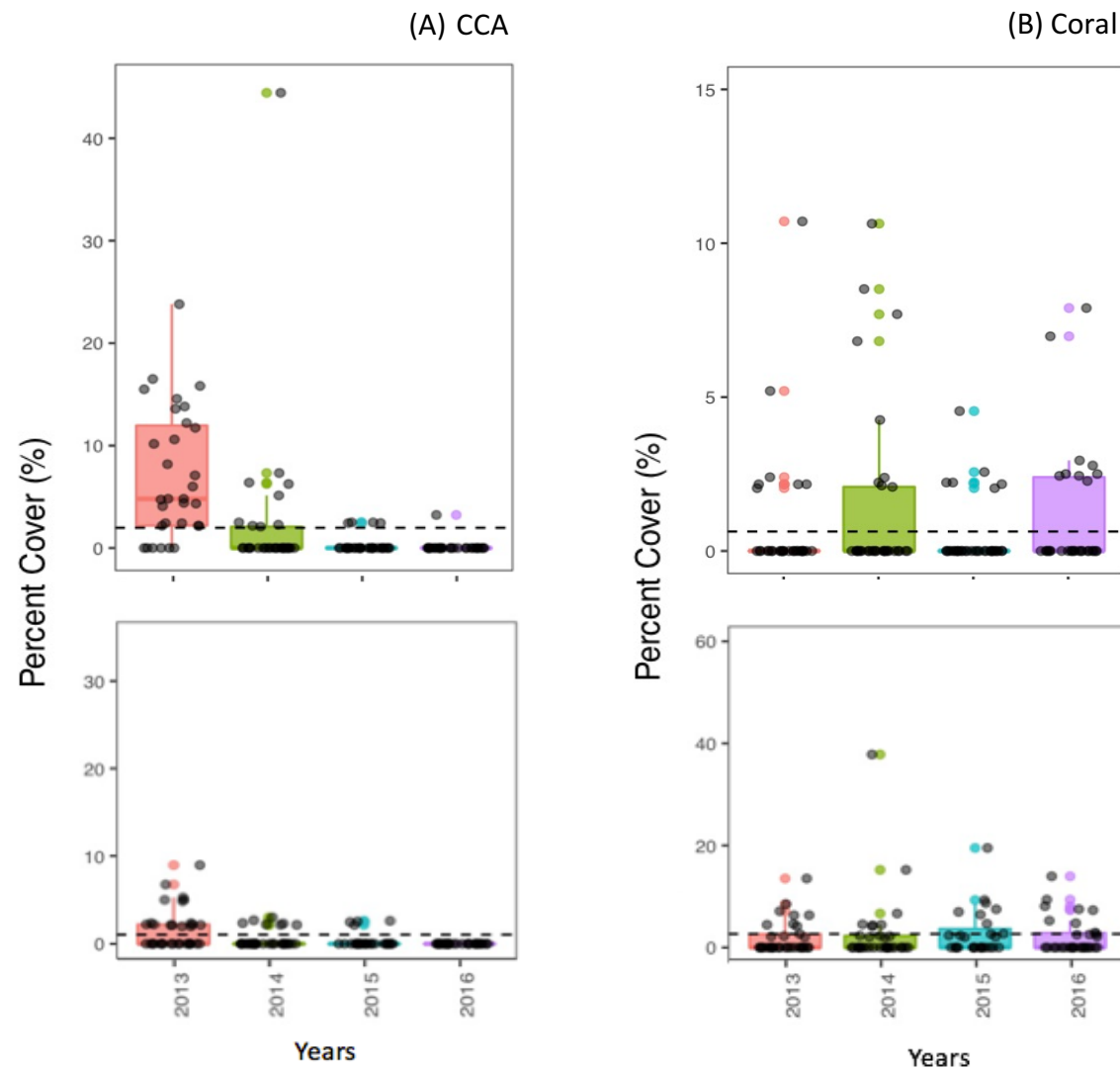


Figure 3. Boxplot graphs illustrating spatio-temporal variability of (A) CCA and (B) corals in Cagarras. Graphs above represent 3-5m range and graphs below represent 9-11m range (mind the vertical scale). Dots represent photoquadrats distribution and the horizontal line is the mean cover of the category for Fernando de Noronha.

Ponta da Sapata

In terms of the major functional groups, Ponta da Sapata resembles Cagarras (Figure 4A). In 2013, there was similar macroalgal and algal turf cover for both depth ranges (cover ~ 45%; Table A2, Appendix S1). CCA and corals also stood out among other categories, with higher covers at 10-12m (Figures 5A and 5B). 2014 and 2015 showed similar benthic community structure, standing out by the increase in algal turf cover to more than 60% and decrease in macroalgal cover to about 30% at both depth ranges. 2014 and 2015 had higher CCA and coral covers at 10-12m, respectively. Lastly, in 2016, algal turf and macroalgal covers resembled (cover ~ 50% and 40%, respectively). CCA showed higher cover at 5-7m this year. Unlike Cagarras, Ponta da Sapata had a slightly higher cover of suspension/filter feeders all over the sampling period.

Within macroalgae subcategories (Figure 4B), in 2013 community was mainly characterized by foliose algae at both depth ranges (48% at 5-7m and 38% at 10-12m). In 2014, macroalgal cover was dominated by filamentous algae at 5-7m (50%) and by articulated calcareous algae at 10-12m (56%). Articulated calcareous algae prevailed in 2015 at both depth ranges (54% at 5-7m and 64% at 10-12m). Finally, in 2016, articulated calcareous algae cover remained dominant at 5-7m (59%), however equated to foliose algae at 10-12m (47%).

ANOSIM analysis for Ponta da Sapata, as well as Cagarras, indicated significant difference between years ($p=0.01$), however not between depths ($p=0.31$). 2013 was significantly different from all of the other years and 2016 was significantly different from 2015 ($R=1$).

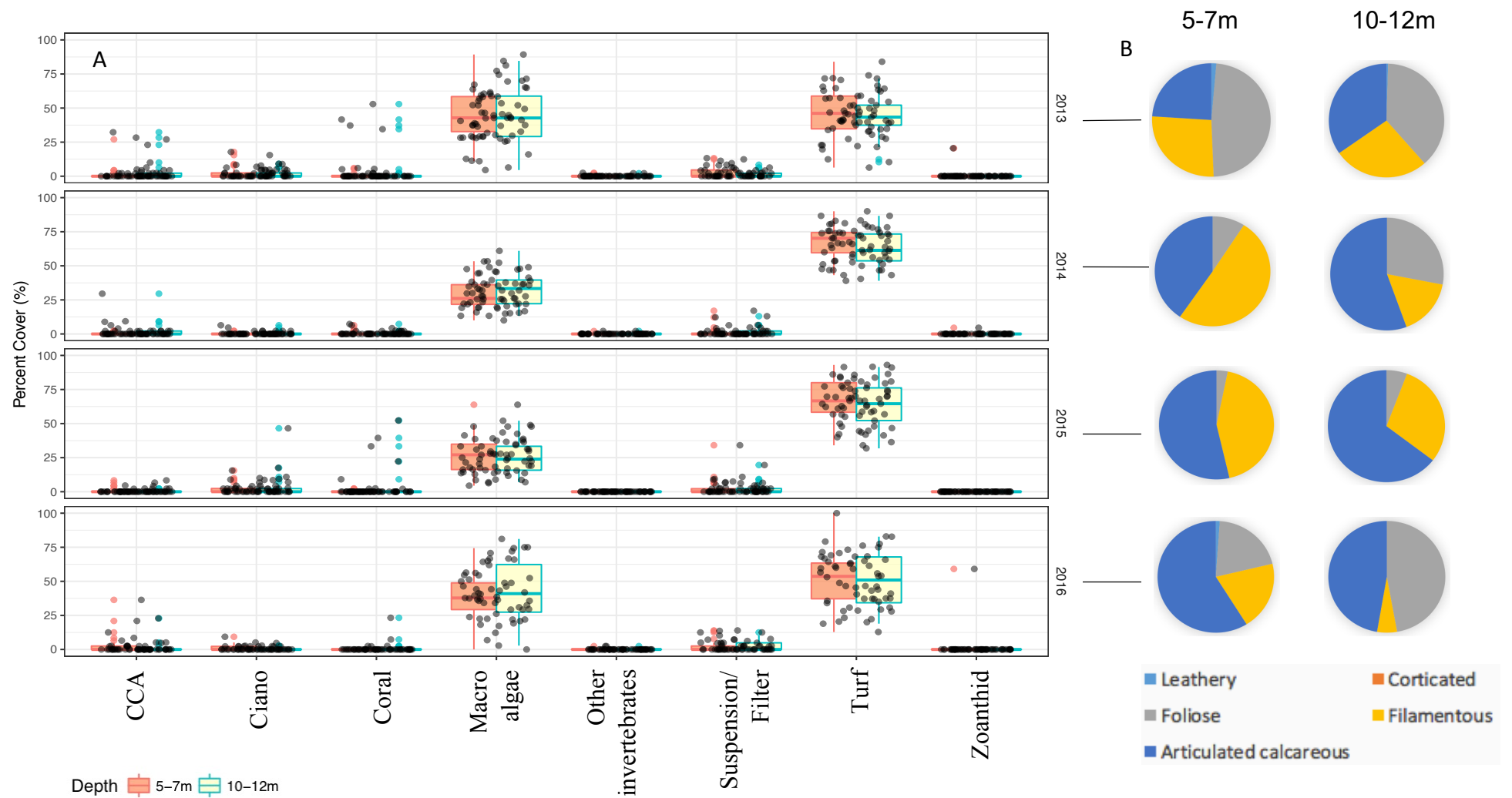


Figure 4. (A) Boxplot graphs illustrating spatio-temporal variability of reef benthic community in Ponta da Sapata. Dots represent photoquadrats distribution. (B) Graphs illustrating macroalgae category composition per depth and year.

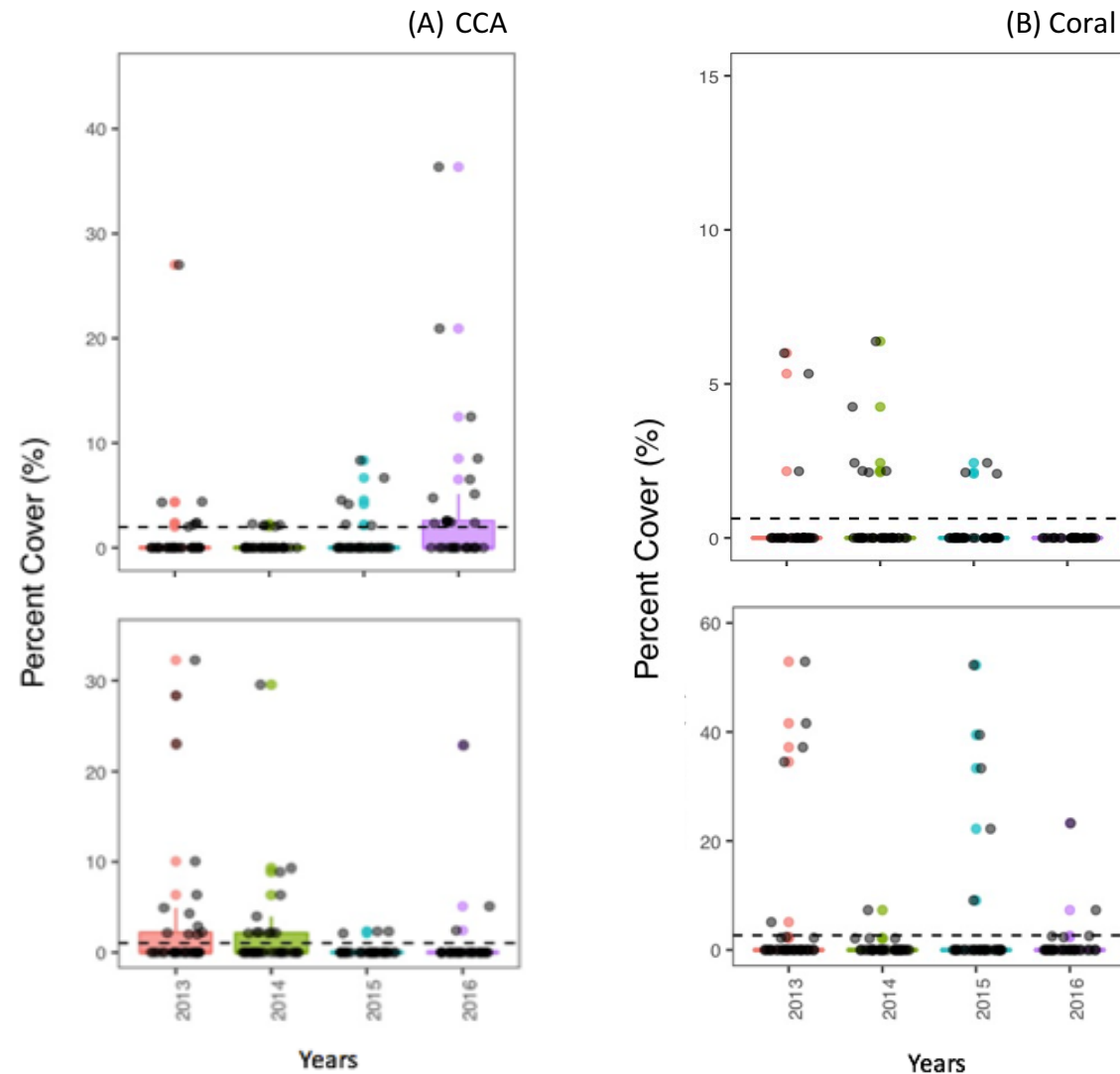


Figure 5. Boxplot graphs illustrating spatio-temporal variability of **(A)** CCA and **(B)** corals in Ponta da Sapata. Graphs above represent 5-7m range and graphs below represent 10-12m range (mind the vertical scale). Dots represent photoquadrats distribution and the horizontal line is the mean cover of the category for Fernando de Noronha.

Laje Dois Irmãos

Laje Dois Irmãos had plentiful macroalgal cover in 2014 for the 11m range, even greater than algal turf cover, unlike the other two sites (Figure 6A). However, in 2015, Laje Dois Irmãos showed similar benthic community structure to the other sites, with macroalgal cover about 35% and algal turf about 60% at 17-21m (table A3, Appendix S1). Macroalgal and algal turf covers resembled in 2016, with about 40% and 50%, respectively. CCA did not vary and corals showed an ascending pattern over the sampling period, with 1.5% in 2014 and 4% in 2016 (Figures 7A and 7B).

Looking into macroalgae subcategories (Figure 6B), it is noticeable that in 2014 this cover was mainly characterized by foliose algae (58%). In 2015, macroalgal cover was dominated by articulated calcareous algae (64%). This functional group increased even more its cover in 2016, representing 82% of all macroalgal cover.

Since Laje Dois Irmãos was sampled at only one depth range per year, ANOSIM analysis for differences between 11m and 17-21m range does not apply. Due to the number of samples, it wasn't possible to calculate differences between years.

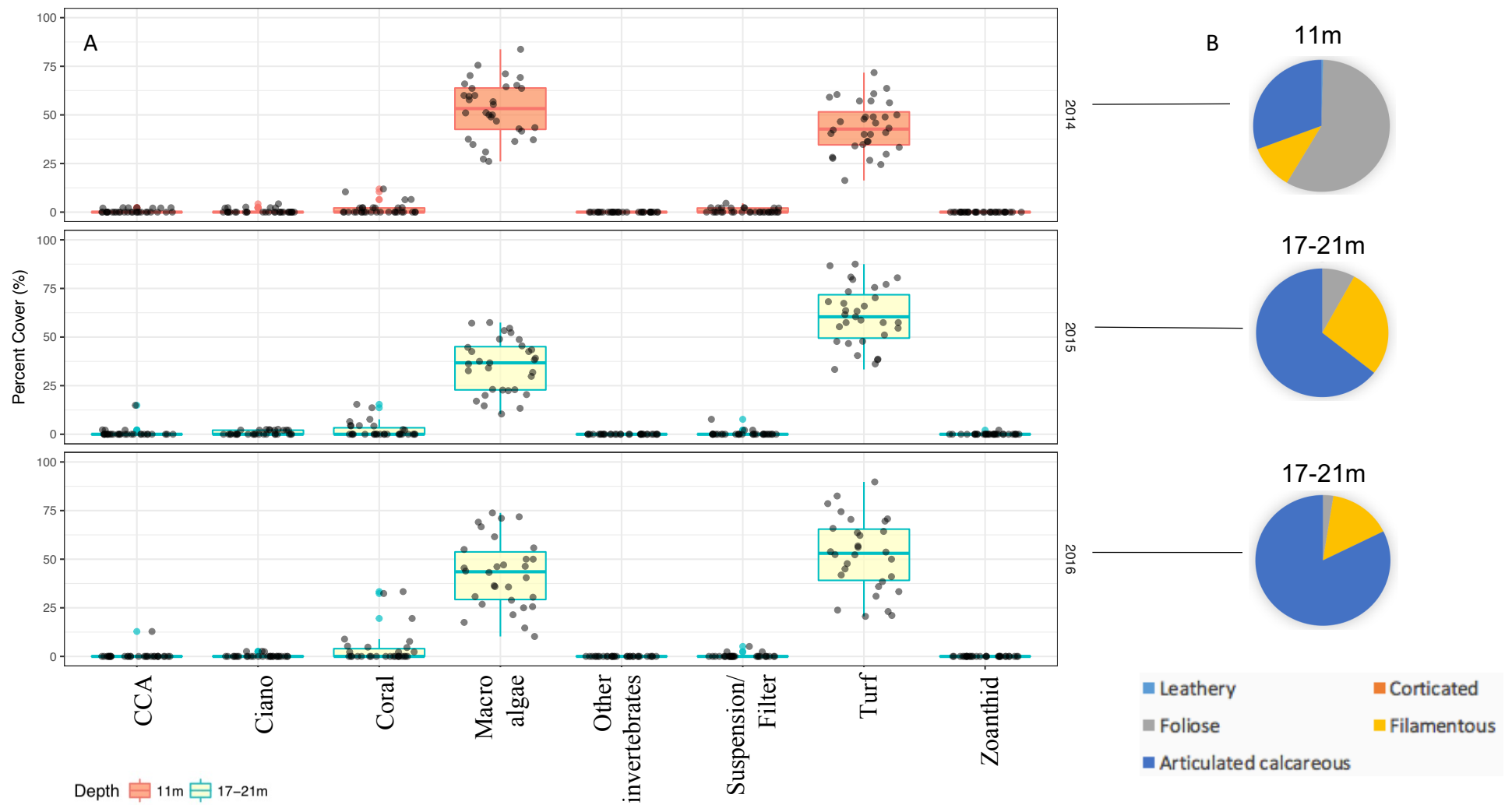


Figure 6. (A) Boxplot graphs illustrating spatio-temporal variability of reef benthic community in Laje Dois Irmãos. Dots represent photoquadrats distribution. (B) Graphs illustrating macroalgae category composition per depth and year.

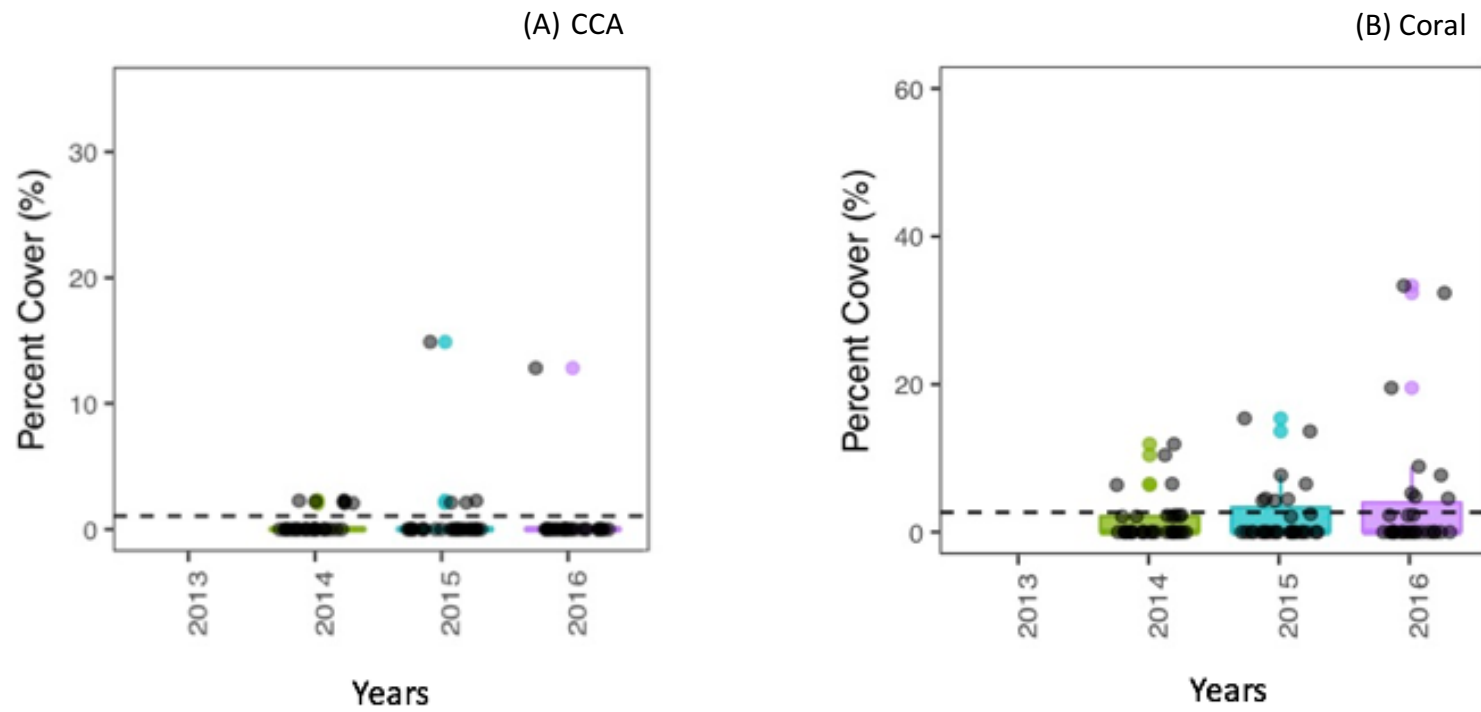


Figure 7. Boxplot graphs illustrating spatio-temporal variability of **(A)** CCA and **(B)** corals in Laje Dois Irmãos (mind the vertical scale). Dots represent photoquadrats distribution and the horizontal line is the mean cover of the category for Fernando de Noronha.

Fernando de Noronha Archipelago

It is noticeable that Fernando de Noronha's reef benthic community has undergone temporal changes over the sampling period for all the three sites and that the main differences were represented by fluctuations on overall cover of algal turf and macroalgae as well as on contribution of each macroalgae subcategory. CCA and corals, even with lower cover, also influenced on differences between years. This result is corroborated by the ANOSIM analysis for Fernando de Noronha as one, which indicates significant community shifts between years and sites (Table 2). Barplot graphs illustrating the community temporal variability in terms of percent cover of functional groups for Fernando de Noronha as one are presented in Figure A1, Appendix S2.

Table 2. ANOSIM results for Fernando de Noronha Archipelago.

<i>Factor</i>	<i>p-value</i>	<i>R-value</i>
<i>Years</i>	0.006	0.22
<i>Sites</i>	0.001	0.39

The nMDS analysis (stress = 0.17) shows sites and their depths distributed throughout the sampling period (Figure 8). It is important to highlight the difference of most 2016 samples for all the three sites, as well as for the 2014 sample for Laje Dois Irmãos (11m) and 2013 sample for Cagarras (3-5m). Overall, samples of 2013, 2014 and 2015 seem to show a variation pattern, especially between 2014 and 2015, while 2016 samples reflect a more pronounced shift.

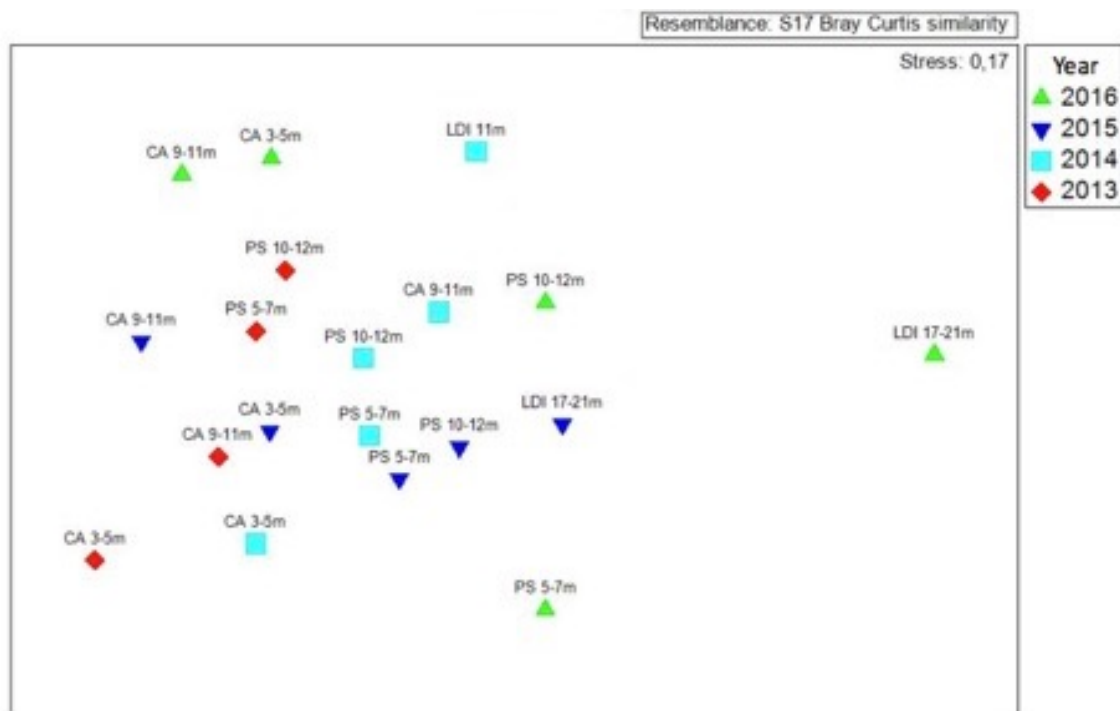


Figure 8. nMDS results for Fernando de Noronha Archipelago showing sites and depths per year. Closer points indicate greater similarity between substrate covers.

The SIMPER analysis pointed a 28.56% dissimilarity between 2013 and 2014 and 29.25% dissimilarity between 2013 and 2015. The decrease in leathery algae (*Sargassum* spp.) at Cagarras and foliose algae (*Dictyota* spp.) at Ponta da Sapata and increase in algal turf cover at both sites from 2013 to 2014 and 2015 were the main responsible for these dissimilarities (Tables 3 and 4). *Dictyopteris* spp. appears with some contribution for this difference as well, representing the high foliose algae cover in Laje Dois Irmãos in 2014. Contribution of *Montastraea cavernosa* may be representing higher coral cover in Ponta da Sapata in 2013 and 2015. 2014 and 2015, in turn, presented the lowest dissimilarity (25.14%). Algal turf and articulated calcareous algae (*Amphiroa* sp. and/or *Jania* sp.) covers were the main responsible for the similarity between these two years (see average abundance of these taxa at tables 5 and 6).

The dissimilarity between 2014 and 2016 was 32.23% and 32.84% between 2015 and 2016. The increase in articulated calcareous algae (*Amphiroa* sp. and/or *Jania* sp.) and foliose algae (*Dictyota* spp.) at all the three sites, especially Ponta da Sapata e Laje Dois Irmãos, and the decrease in algal turf cover from 2014 to 2015 and 2016 were the main responsible for these dissimilarities. Increase in exposed rock area and sand cover has also contributed (Tables 5 and 6). Finally, 2013 and 2016 appeared to be the most different years, with dissimilarity of 35.39%.

Table 3. SIMPER results for Fernando de Noronha Archipelago between 2013 and 2014 communities.

<i>Taxon</i>	2013		2014
	<i>Av.Abund</i>	<i>Av.Abund</i>	<i>Contrib.</i>
Turf	65%	75.6%	18.24%
<i>Sargassum</i> spp.	8.45%	0.34%	6.91%
<i>Dictyota</i> spp.	16.19%	11.12%	6.45%
<i>Dictyopteris</i> spp.	3.44%	5.39%	5.41%

Table 4. SIMPER results for Fernando de Noronha Archipelago between 2013 and 2015 communities.

<i>Taxon</i>	2013		2015
	<i>Av.Abund</i>	<i>Av.Abund</i>	<i>Contrib.</i>
Turf	65%	73.5%	16.9%
<i>Dictyota</i> spp.	16.19%	7.22%	7.78%
<i>Sargassum</i> spp.	8.45%	0%	6.94%
<i>Montastraea cavernosa</i>	4.01%	4.93%	4.52%

Table 5. SIMPER results for Fernando de Noronha Archipelago between 2014 and 2016 communities.

<i>Taxon</i>	2014		2016
	<i>Av.Abund</i>	<i>Av.Abund</i>	<i>Contrib.</i>
Turf	75.6%	60.6%	18.05%
<i>Amphiroa</i> sp./ <i>Jania</i> sp.	12.26%	18.56%	8.16%
<i>Dictyota</i> spp.	11.12%	16.04%	6.96%
Exposed rock/sand	7.33%	15.13%	6.54%

Table 6. SIMPER results for Fernando de Noronha Archipelago between 2015 and 2016 communities.

<i>Taxon</i>	2015	2016	<i>Contrib.</i>
	<i>Av.Abund</i>	<i>Av.Abund</i>	
Turf	73.5%	60.%	16.69%
<i>Dictyota</i> spp.	7.22%	16.04%	8.59%
Exposed rock/sand	4.7%	15.13%	8.59%
<i>Amphiroa</i> sp./ Jania sp.	12.15%	18.56%	8.30%

Lastly, temperature data analysis (Figure 9) showed interannual variability on sea surface temperature for Fernando de Noronha Archipelago. 2013 appears to have experienced the highest temperatures during the months preceding the sampling, especially from July. 2014 seems to have experienced, overall, lower temperatures than 2013. 2015 showed the lowest mean temperature, especially during the months preceding the sampling, between May and August. 2015 has also experienced higher temperatures from November, followed by the higher temperatures from January to March 2016, possibly indicating temperature anomalies from the ENSO event. This period showed several temperature peaks from 28°C to more than 29°C, while previous years showed temperatures between 26°C and 28°C. Except for the period from January to March and from November onwards, 2016 appears to have experienced similar mean temperature to 2013.

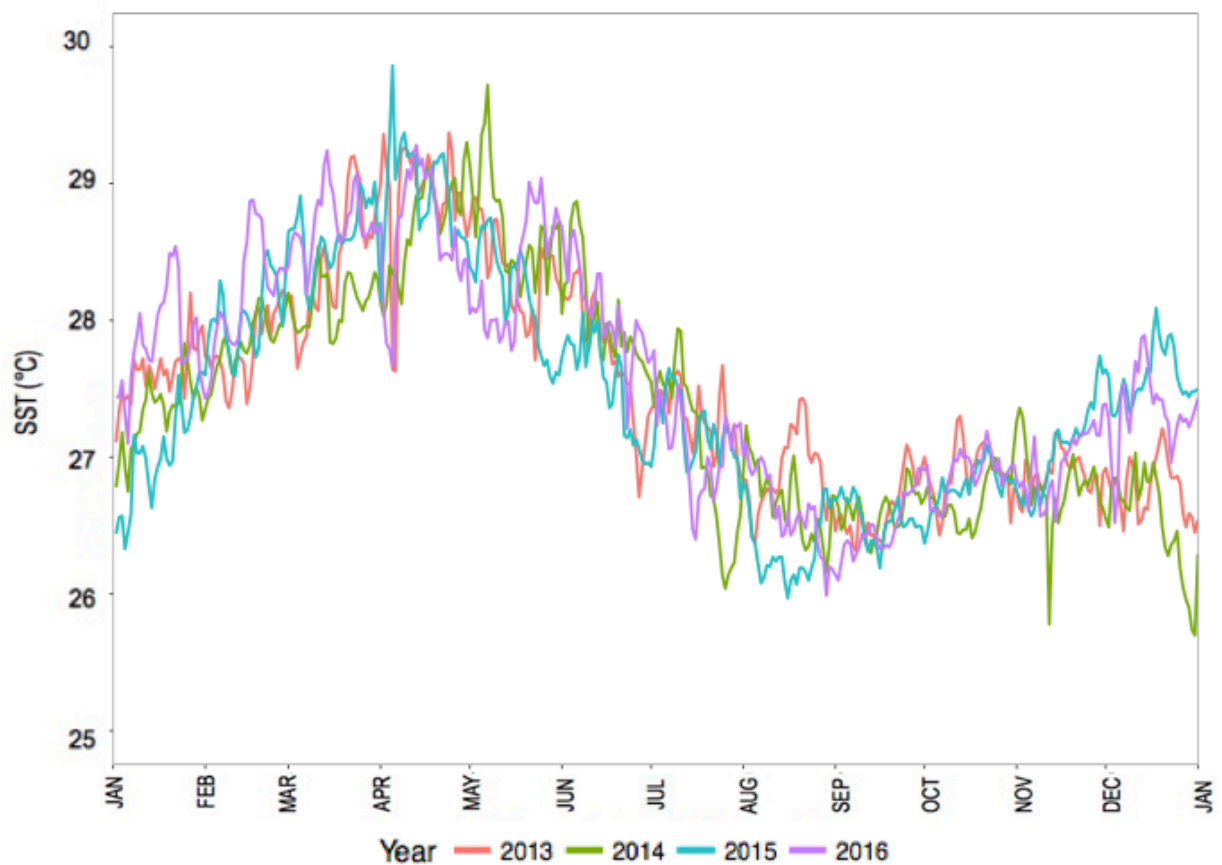


Figure 9. Sea surface temperature for Fernando de Noronha Archipelago region on each sampling year.

Discussion

Our results revealed that, overall, reef benthic community of Fernando de Noronha Archipelago is mainly composed by algal turf and macroalgae, especially from the genera *Dictyota*, *Sargassum*, *Dictyopteris* and *Amphiroa* and/or *Jania*. CCA and corals were also relevant and, in the latter case, *Montastraea cavernosa* stood out among other species, which is consistent with the pre-existing literature (Eston et al. 1986; Pires et al. 1992; Ferreira et al. 2006; Krajewski and Floeter 2011). In terms of functional groups, reef benthic community was consistent between sites. However, at the genus taxonomic level, there were significant differences, especially in terms of macroalgae category composition. Cagarras was the only site to show *Sargassum* spp. cover. Ponta da Sapata and Laje Dois Irmãos, in turn, showed plentiful *Dictyota* spp. and *Dictyopteris* spp., respectively, as well as articulated calcareous algae. There was no significant difference between depths at each site, though.

In terms of temporal variability, our results showed that reef benthic community of Fernando de Noronha Archipelago has undergone shifts over the sampling period. Overall, algal turf showed cover higher than 40% at all sites for all the sampling period. However, in 2013 and 2016 this cover resembled macroalgal cover, while in 2014 and 2015 it represented more than 60% of the substrate cover at the three sites. 2016 stood out by higher cover of articulated calcareous algae, exposed rock and sand. CCA and corals represented less than 5% of the total cover at the three sites, except for Cagarras in 2013, when CCA cover reached 7%. These functional groups did not show a clear temporal variation pattern.

Community Composition and Spatial Variability

Firstly, our results showed that there was no significant difference between depths for Cagarras and Ponta da Sapata. This is probably due to the homogeneity of the water column over the sampled depths, especially in terms of light penetration, considering the clear waters at oceanic islands, which makes benthic community distribution homogeneous as well.

Cagarras was the only sampled site to show dominance of *Sargassum* spp. cover and it might be related to its geomorphological shape. This site is located into a sheltered bay (Figure 1) and although it undergoes influence of wave action during north-westerly swells (Krajewski and Floeter 2011), it is probably much more protected to wind and swell action than the other sites. *Sargassum* spp. is a common macroalga in the intertidal zone of Fernando de Noronha Archipelago (Pereira 2006), however it is an organism that does not tolerate much disturbance (Steneck and Dethier 1994), what makes Cagarras a propitious spot for its settlement.

Ponta da Sapata, on the other hand, is a more exposed site, receiving direct wind and swell action, especially from November to March, when prevailing swell is from northwest. Unlike Cagarras, Ponta da Sapata showed plentiful *Dictyota* spp. and *Amphiroa* sp. and/or *Jania* sp. cover, the latter one quite resistant to physical disturbances (Littler and Littler 1980). Ponta da Sapata was also the only site to show higher suspension/filter-feeder cover over all the sampling period. Sponges, specifically, are known for resisting several disturbances and regenerate after damages (Wulff 2006). The presence of more resistant organisms might indicate higher exposure of this site.

Lastly, Laje Dois Irmãos was the deeper site to be sampled in 2015 and 2016. This site has a typical geomorphological shape quite different from the other sites, presenting a steeper slope. Laje Dois Irmãos is also known for having, besides Sancho beach, the highest coral cover of Fernando de Noronha Archipelago (about 20%) (Krajewski and Floeter 2011), probably due

to this greater depth, which reduces physical impact of waves on the reef (Storlazzi et al. 2002). This higher coral cover may also influence on overall carbonate availability and could explain the highest *Amphiroa* sp. and/or *Jania* sp. covers at this site. However, our results show less than 5% coral cover at this site for all the sampling period, much lower than reported by Krajewski and Floeter (2011). Despite some methodological differences, the difference in coral cover may indicate a decrease of this functional group and possible relation with high algal turf and macroalgal cover observed in this site over the sampling period. As mentioned previously, except for Laje Dois Irmãos and Sancho beach, reefs of Fernando de Noronha Archipelago show, overall, low coral cover (0-5%) (Krajewski and Floeter 2011), so our results for Cagarras and Ponta da Sapata are consistent with pre-existing literature.

The overall reef benthic community structure of Fernando de Noronha Archipelago is also comparable with those of other oceanic islands. Longo et al. (2015), for example, reported reef benthic community of open pools of Rocas Atoll as being, overall, dominated by algal turf, composed primarily by articulated calcareous algae. The authors also highlight *Caulerpa verticillata* within macroalgae category and *Siderastrea stellata* among corals. Similarly, Magalhães et al. (2015) recorded plentiful algal turf at the euphotic zone of St. Peter and St. Paul Archipelago, as well as *Caulerpa racemosa* var. *peltata*, *Bryopsis* spp. and *Dictyota menstrualis* within macroalgae category and the zoanthid *Palythoa caribaeorum*. Meirelles et al. (2015) also recorded plentiful algal turf cover on rocky reefs of Trindade Island, however highlight the abundance of CCA and rhodolith beds at other seamounts of Vitoria-Trindade seamount chain. The authors also highlight *Montastraea cavernosa* and *Siderastrea* sp. among dominant coral species.

Temporal Variability

Based on the assumption that this is a community mainly composed by algae and that algal assemblages tend to change seasonally or even within and between years (Steneck and Dethier 1994; Vroom and Braun 2010), changes observed in this study may be only a reflection of this natural dynamics. Besides that, Fernando de Noronha Archipelago may be subject to high and variable hydrodynamic, typical feature of oceanic habitats (Linsker 2003), and it can result in a very dynamic benthic community. In addition, since fishing activities are restricted up to 50m deep (Linsker 2003), there is no register of changes in herbivorous fish community. Nonetheless, it is also possible to infer some correlations with external stressors, specially due to the spatial pattern present in this variation.

Temperature data analysis showed that, in 2013, Fernando de Noronha Archipelago experienced slightly higher temperatures during the months preceding the sampling than 2014. However, Assunção et al. (2016), studying sea surface thermohaline properties around Fernando de Noronha Archipelago, pointed out that there was no significant difference on sea surface temperature between 2013 and 2014. Still, the authors show that 2014 experienced much less rain than 2013 from June to August, especially during July, period usually known for higher precipitation rates (rainy season). While the average precipitation for July 2013 was around 9.5mm, the same month in 2014 experienced almost 70% less rain than the previous year (Assunção et al. 2016), and it might be related to the lower sea surface temperatures recorded for this month (Figure 9). As mentioned previously, *Sargassum* spp. does not tolerate much disturbance and, according to Pereira (2006), decline in its cover may be related to low nutrient availability. Indeed, macroalgae in general depend on nutrient availability for their maintenance. Considering the high drainage levels during rainy periods, it is possible to infer that the decrease in macroalgal cover from 2013 to 2014 has been caused by the lower precipitation in 2014 and consequent lower nutrient availability due to the lower drainage, especially in a region of oligotrophic waters such as oceanic islands, which depends on land runoff for enrichment. As mentioned previously, Laje Dois Irmãos seemed not to have been affected in 2014, presenting dominance of *Dictyopteris* spp. In 2015, on the other hand, this site also showed lower macroalgal cover and higher algal turf cover.

Fernando de Noronha benthic community was quite similar in 2014 and 2015. Despite the temperature differences pointed out in Figure 9, especially during months preceding the sampling, benthic community during these two years was mainly composed by algal turf. This functional group is known for being opportunistic and for replace macroalgal biomass after disturbances (Steneck and Dethier 1994), and it might explain its significant increase after *Sargassum* spp. and *Dictyota* spp. decrease in Cagarras and Ponta da Sapata, respectively. Although algal turfs also depend on nutrient availability, this functional group seems to be more resistant to less nutrient availability than macroalgae (Rasher et al. 2012).

Indeed, 2014 and 2015 were the years that showed the highest algal turf cover (>60%), however this functional group also had high cover (>40%) in 2013 and 2016 and it may reflect a characteristic of this community. Aued et al (in prep.), studying the benthic cover over all the Brazilian coast and Brazilian oceanic islands (except for St. Peter and St. Paul Archipelago), noticed that algal turf was a very abundant functional group all over the sampling sites (national mean cover ~ 52%). Our results show that, even with fluctuations, this high cover was persistent for Fernando de Noronha Archipelago for the sampled period.

The year of 2016 stood out among other sampled years for having the most different benthic community structure. This year showed decrease in algal turf and increase in macroalgal cover, especially articulated calcareous algae, as well as more exposed rocks and sand cover. Besides being quite resistant to physical disturbances, articulated calcareous algae have the ability to rapidly occupy the substrate from the remaining crusty base after those disturbances (Konar and Foster 1992). The temperature data show a great increase in sea surface temperature around Fernando de Noronha Archipelago from November 2015 to March 2016, possibly indicating temperature anomalies from the ENSO 2015/2016 event. According to Linsker (2003), mean sea surface temperature around Fernando de Noronha Archipelago is about 27°C and the period from November 2015 to March 2016 showed several temperature peaks from 28°C to more than 29°C, quite different from the same period of previous years. Besides that, there are records¹ of strong northwest swells in October 2016. High cover of articulated calcareous algae in Ponta da Sapata and Laje Dois Irmãos may have been a response to higher temperatures and strong wave action disturbance combined with substrate availability, considering algal turf dominance until that moment. Strong wave action might also explain higher exposed rocks and sand cover in 2016.

Cagarras did not show high cover of articulated calcareous algae, instead its benthic community in 2016 was mainly composed by *Dictyota* spp., possibly because of the lower wave exposure of this site. Nonetheless, it was still affected by changes in temperature, what may be indicated by the presence of *Dictyota* spp. instead of *Sargassum* spp. as in 2013. According to Guimaraens and Coutinho (1995), *Dictyota* spp. tends to be favoured by warm waters, while *Sargassum* spp. is influenced by lower temperatures (Vroom and Braun 2010). Regarding overall CCA and coral cover fluctuations, CCA showed higher cover in 2013 at both depth ranges, followed by 2015 at the deeper range and by 2016 at the shallower range, whereas corals showed higher cover in 2013, 2015 and 2016 at the deeper range (Figure A1, Appendix S2). It did not show a clear correlation with the external stressors considered, with low variation over the sampled period, so it may be consequence of more or less algal turf and macroalgal cover, which can cover these encrusting categories.

Despite the fact that changes observed in Fernando de Noronha Archipelago reef benthic community may be a reflection of its own natural dynamics, it is important to highlight the possible influence of the ENSO 2015/2016 event, especially due to the significant difference of 2016 towards the previous years. The ENSO event produces anomalies on sea surface

¹ Ana Clara Marinho, Globo Comunicação e Participações S.A. (2016)

temperature and can lead to bleaching events and phase-shifts on reef communities all around the world, including Brazil (Hughes et al. 2003; Leão, Kikuchi and Oliveira 2008). Impacts of this climate event were even recorded at Fernando de Noronha Archipelago after ENSO 2002/2003 (Ferreira et al. 2006) and ENSO 2009/2010 (Ferreira et al. 2013). 2016 showed the greatest area with positive temperature anomaly ($+0.5^{\circ}\text{C}$) in the Atlantic Ocean among the sampled years, encompassing the entire archipelago region, while 2015 showed negative anomaly (-0.5°C) for this region (Estados Unidos 2016). Indeed, our temperature data analysis showed higher temperatures from November 2015 to March 2016 and, even though we have not tested the correlation significance between this variation and changes on benthic community structure, changes observed in this study for 2016 are very likely to be induced by this climate event.

Influences of ENSO events have been well recorded in reef communities of the Great Barrier Reef, Caribbean and some regions of the Indo-Pacific (HUGHES et al. 2017). However, even though there are records of bleaching events and recovery on South Atlantic reefs, long-term studies about damages of this climate event on reef benthic communities in this region are still incipient. As mentioned previously, only spatial characterization or short-term assessment (seasonal and interannual) of reef benthic community on Brazilian oceanic islands have been described and the lack of methodological standardization between different studies hampers the assessment of temporal shifts and of the influence of stressors such as the ENSO event. As a result, studies about the resilience capacity of reef benthic community towards those stressors are also hampered, since the assessment of phase-shifts on these communities requires a long-term monitoring.

Even though the present study does not comprise a long term monitoring, it may be a first step towards filling this temporal gap in the studies of Brazilian oceanic islands reef communities. Indeed, it will require continuity on samplings and data analyses, as well as further analyses of oceanographic parameters, such as temperature, pH, salinity and chlorophyll, and the linkage of these variables with the changes observed in the benthic community.

Acknowledgments

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Appendix S1 – Mean cover and standard deviation of all categories identified in this study

Table A1. Mean cover and standard deviation of all categories identified in Cagarras per depth and year.

Mean Cover and Standard Deviation (%)

<i>Categories</i>	<i>Depth (m)</i>	<i>2013</i>	<i>2014</i>	<i>2015</i>	<i>2016</i>
CCA	3-5	7 ± 2.1	2.2 ± 1.5	0.3 ± 0.4	0.1 ± 0.1
	9-11	1.7 ± 0.7	0.5 ± 0.3	0.3 ± 0.3	0.0 ± 0.0
Ciano	3-5	1.8 ± 0.6	0.3 ± 0.2	0.3 ± 0.2	0.2 ± 0.1
	9-11	1.6 ± 1.7	0.3 ± 0.2	0.3 ± 0.2	0.1 ± 0.1
Coral	3-5	0.9 ± 0.4	1.4 ± 1.3	0.5 ± 0.4	1.1 ± 0.2
	9-11	1.9 ± 1.1	2.7 ± 1.0	3.2 ± 1.9	2.3 ± 1.2
Macroalgae	3-5	41.1 ± 7.1	17.9 ± 3.6	32.0 ± 7.0	49.2 ± 11.3
	9-11	29.7 ± 5.4	25.1 ± 5.6	38.9 ± 7.7	45.9 ± 8.9
Other invertebrates	3-5	1.7 ± 1.0	3.0 ± 1.8	0.3 ± 0.1	0.0 ± 0.0
	9-11	1.5 ± 0.8	0.7 ± 0.4	2.2 ± 0.9	0.0 ± 0.0
Suspension/ Filter feeders	3-5	1.6 ± 0.1	0.4 ± 0.3	0.1 ± 0.2	0.3 ± 0.4
	9-11	1.4 ± 0.9	0.2 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
Turf	3-5	45.8 ± 12.1	74.7 ± 3.7	66.5 ± 6.6	49.1 ± 7.6
	9-11	62.1 ± 3.7	70.6 ± 3.6	55.1 ± 5.9	51.7 ± 3.8
Zoanthid	3-5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	9-11	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Appendix S1 – Mean cover and standard deviation of all categories identified in this study

Table A2. Mean cover and standard deviation of all categories identified in Ponta da Sapata per depth and year.

Mean Cover and Standard Deviation (%)

<i>Categories</i>	<i>Depth (m)</i>	<i>2013</i>	<i>2014</i>	<i>2015</i>	<i>2016</i>
CCA	5-7	1.3 ± 0.9	0.3 ± 0.2	0.9 ± 0.7	3.8 ± 3.6
	10-12	3.7 ± 3.7	2.2 ± 0.9	0.2 ± 0.2	1.1 ± 1.1
Ciano	5-7	2.6 ± 3.0	0.1 ± 0.1	2.5 ± 1.0	1.4 ± 0.8
	10-12	1.7 ± 0.4	0.6 ± 0.6	3.4 ± 2.4	0.3 ± 0.2
Coral	5-7	1.0 ± 1.0	0.7 ± 0.5	0.2 ± 0.0	2.0 ± 2.8
	10-12	5.4 ± 6.9	0.4 ± 0.4	4.8 ± 6.8	1,2 ± 1.1
Macroalgae	5-7	45.7 ± 8.6	29.7 ± 6.6	27.0 ± 7.0	38.9 ± 8.9
	10-12	43.8 ± 7.4	32.8 ± 7.0	25.1 ± 6.6	44.1 ± 10.0
Other invertebrates	5-7	0.1 ± 0.1	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.1
	10-12	0.1 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.1
Suspension/ Filter feeders	5-7	2.9 ± 0.6	1.2 ± 0.8	2.7 ± 1.1	2.4 ± 1.9
	10-12	1.4 ± 0.1	1.5 ± 0.7	2.1 ± 0.5	2.6 ± 1.2
Turf	5-7	46.3 ± 10.1	67.8 ± 3.3	66.7 ± 7.9	51.4 ± 8.5
	10-12	43.9 ± 4.7	62.5 ± 3.1	64.4 ± 7.2	50.6 ± 4.2
Zoanthid	5-7	0.6 ± 0.9	0.1 ± 0.2	0.0 ± 0.0	2.0 ± 1.9
	10-12	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

Appendix S1 – Mean cover and standard deviation of all categories identified in this study

Table A3. Mean cover and standard deviation of all categories identified in Laje Dois Irmãos per depth and year.

<i>Mean Cover and Standard Deviation (%)</i>				
<i>Categories</i>	<i>Depth (m)</i>	<i>2014</i>	<i>2015</i>	<i>2016</i>
CCA	11m	0.5 ± 0.2	-	-
	17-21m	-	0.7 ± 0.7	0.4 ± 0.6
Ciano	11m	0.5 ± 0.4	-	-
	17-21m	-	0.7 ± 0.5	0.3 ± 0.0
Coral	11m	1.5 ± 0.7	-	-
	17-21m	-	2.0 ± 0.8	4.0 ± 1.7
Macroalgae	11m	52.8 ± 11.8	-	-
	17-21m	-	35.5 ± 9.2	42.5 ± 13.8
Other invertebrates	11m	0.0 ± 0.0	-	-
	17-21m	-	0.0 ± 0.0	0.0 ± 0.0
Suspension/ Filter feeders	11m	0.7 ± 0.4	-	-
	17-21m	-	0.3 ± 0.3	0.3 ± 0.4
Turf	11m	43.9 ± 3.9	-	-
	17-21m	-	60.7 ± 2.9	52.4 ± 5.2
Zoanthid	11m	0.0 ± 0.0	-	-
	17-21m	-	0.1 ± 0.1	0.0 ± 0.0

Appendix S2 - Community temporal variability in terms of percent cover of functional groups for Fernando de Noronha Archipelago

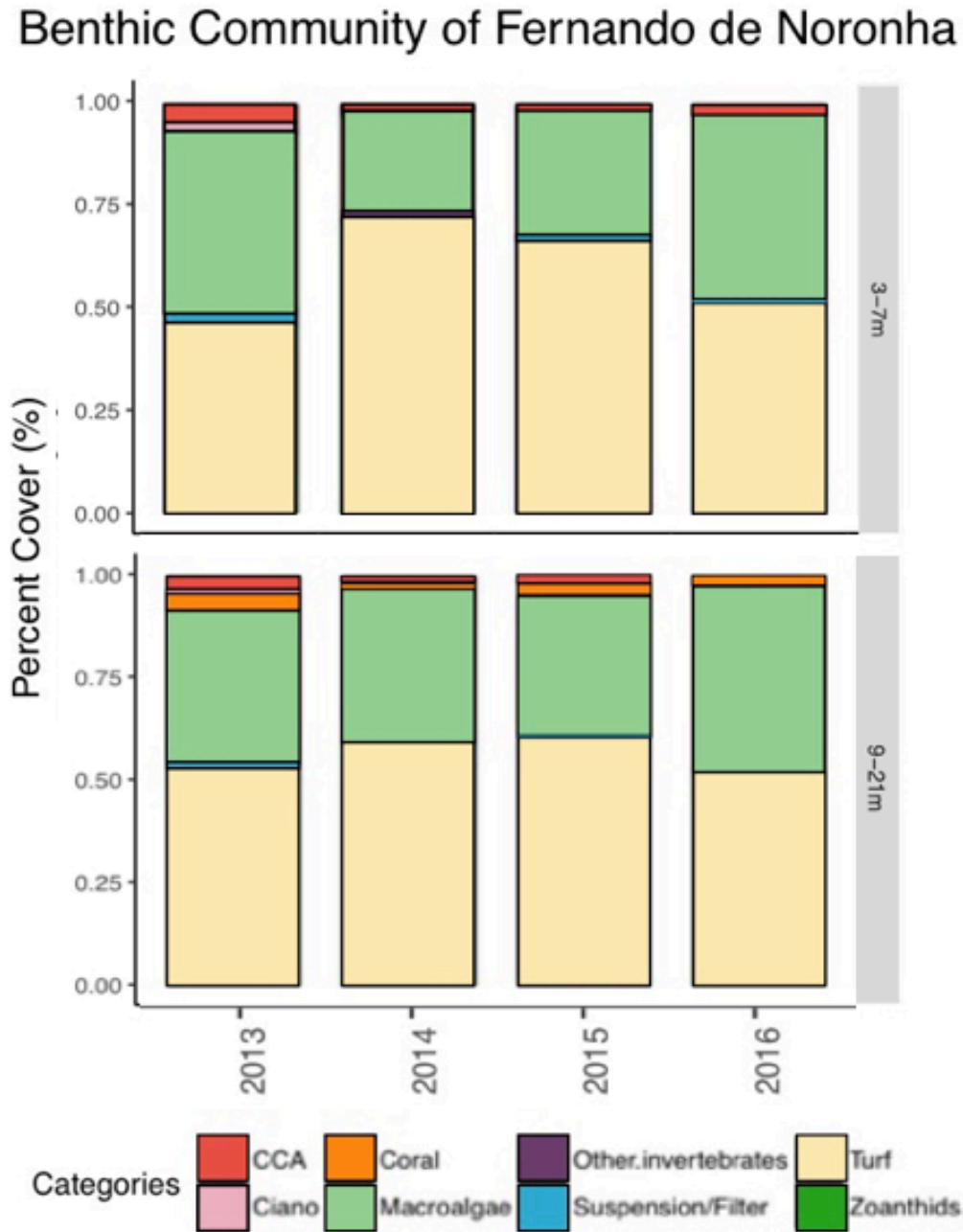


Figure A1. Barplot graph illustrating the community temporal variability in terms of percent cover of functional groups for Fernando de Noronha Archipelago. Mean values were calculated by separating data into two depth ranges within the minimum and maximum settled for the three sites (both sampling depths of Laje Dois Irmãos were included in the deeper range).

CONCLUSÃO GERAL

Os resultados obtidos neste estudo mostraram que a comunidade bentônica recifal do Arquipélago de Fernando de Noronha é predominantemente composta por *turf* e macroalgas, corroborando com a literatura pré-existente. Em termos de grupos morfofuncionais, a comunidade bentônica recifal foi, de maneira geral, consistente entre os sítios. Todavia, em nível taxonômico de gênero, os sítios amostrados apresentaram diferença significativa entre suas comunidades, em especial na composição da categoria de macroalgas, o que pode estar relacionado à maior ou menor exposição à ação de ventos e *swell*.

As análises realizadas apontaram também a existência de uma variação temporal na comunidade bentônica recifal do arquipélago para o período amostrado, com diferença significativa entre os anos, especialmente 2016. De maneira geral, *turf* apresentou cobertura maior que 40% em todos os sítios ao longo dos anos de amostragem. Todavia, em 2013 e em 2016 essa cobertura assemelhou-se a cobertura de macroalgas, ao passo que em 2014 e 2015 representou mais de 60% da cobertura do substrato nos três sítios. CCA e corais representaram menos de 5% da cobertura nos três sítios, com exceção de Cagarras em 2013, quando a cobertura de CCA atingiu 7%. Ainda assim, esses grupos também apresentaram variação temporal, possivelmente relacionada a maior ou menor cobertura de *turf* e macroalgas, as quais recobrem esses grupos mais rasteiros.

Ainda que comunidades predominantemente compostas por algas sejam naturalmente dinâmicas e as variações observadas neste estudo possam ser apenas o reflexo dessa característica, foi possível estabelecer relações com alguns fatores de estresse. Supõe-se que a variação na comunidade bentônica recifal do arquipélago entre 2013 e 2014 esteja relacionada à diferença de precipitação entre esses anos e à consequente diferença de aporte terrígeno e disponibilidade de nutrientes. O aumento da cobertura de *turf*, a qual permaneceu em 2015, pode estar então relacionado ao comportamento oportunista desse grupo morfofuncional, conhecido por substituir rapidamente a biomassa de macroalgas após algum distúrbio.

Supõe-se que a variação observada na comunidade entre 2015 e 2016, por sua vez, tenha relação com as anomalias de temperatura da superfície do mar (TSM) ocasionadas pelo evento ENSO 2015/2016 e a fortes eventos de *swell*. 2016 apresentou elevada cobertura de macroalgas calcárias articuladas, conhecidas por sua resistência a distúrbios e por sua capacidade de rapidamente ocupar o substrato a partir da base crostosa remanescente. De fato, os dados de temperatura apontaram altos valores de TSM de novembro de 2015 a março de 2016 e apesar

de a correlação entre esse aumento e a variação na comunidade não ter sido testada, muito provavelmente ela foi influenciada por esse evento climático.

Influências do evento ENSO já foram registradas em comunidades recifais de várias regiões do globo, como Grande Barreira de Corais, Caribe e regiões do Indo-Pacífico e, apesar de haverem alguns registros de branqueamento e recuperação no Atlântico Sul, estudos prolongados dos efeitos desse evento na região são ainda incipientes. A falta de padronização metodológica entre diferentes estudos dificulta a avaliação de variações temporais como mudanças de fase, por exemplo, e, conseqüentemente, a compreensão da capacidade de resiliência de comunidades bentônicas recifais frente a estressores como o evento ENSO.

Ainda que o presente estudo não configure um monitoramento a longo prazo, ele pode ser o primeiro passo para dar início ao preenchimento dessa lacuna temporal em estudos sobre comunidades bentônicas recifais em ilhas oceânicas brasileiras. Para tanto, é necessário a continuidade das amostragens e análises de dados, assim como análises mais aprofundadas de parâmetros oceanográficos, como temperatura, pH, salinidade e clorofila, e de sua correlação com as variações observadas na comunidade bentônica.