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VARIAÇÕES INTRA E INTERESPECÍFICAS NAS ESTRATÉGIAS DE FORRAGEIO DE *Sula* spp. (SULIFORMES: SULIDAE) NO OCEANO ATLÂNTICO TROPICAL

PORTO ALEGRE
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Dissertação apresentada ao Programa de Pós-Graduação em Biologia Animal, Instituto de Biociências da Universidade Federal do Rio Grande do Sul, como requisito parcial à obtenção do título de Mestre em Biologia Animal.

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SUMÁRIO

RESUMO

Oceanos tropicais são ambientes tipicamente oligotróficos, com recursos distribuídos de forma irregular no espaço e no tempo. Essa irregularidade na disponibilidade de presas faz com que adaptações em estratégias de forrageio e partição de nicho sejam essenciais para a sobrevivência de predadores, como as aves marinhas. Esse grupo tende a se reproduzir em colônias multiespecíficas e utiliza recursos no entorno da colônia, especialmente durante o período reprodutivo. A reprodução representa um momento intensa exploração de recursos para suprir demandas energéticas dos pais e do filhote. Assim, um comportamento de forrageio plástico permite que as aves marinhas se adaptem a variações espaço-temporais tanto em nível intra quanto interespecífico. Nesse contexto, o presente trabalho procurou caracterizar as estratégias de forrageio de aves marinhas do gênero *Sula* no arquipélago de Fernando de Noronha em níveis intra e interespecífico, utilizando dados de rastreamento remoto e isótopos estáveis de carbono (δ^{13}C) e nitrogênio (δ^{15}N) obtidos entre 2015 e 2022. Para o atobá-mascarado (*Sula dactylatra*, MB) foi observado um padrão interanual da área de forrageio a leste do arquipélago, potencialmente associado à interação de correntes com a topografia local, que gera um fluxo de correntes ascendentes nessa região. Entretanto, em 2022 a área de forrageio foi reduzida e concentrada próxima ao arquipélago em relação aos anos anteriores. Além disso, não houve sobreposição de nicho isotópico desse ano com os demais e a proporção de contribuição de presas para a dieta se alterou. Essa variação interanual pode ser consequência de fatores oceanográficos locais ou também de distribuição de predadores pelágicos com os quais aves marinhas se associam durante o forrageio. Esses resultados demonstram a plasticidade trófica de MB ao adaptar suas áreas de forrageio frente a variações interanuais em um ambiente tropical, evidenciando o potencial dessas aves como monitoras de variações de distribuição e composição de peixes epipelágicos. Posteriormente, foram testadas variações no nicho isotópico entre MB e o atobá-de-pé-vermelho (*Sula sula*, RFB) entre períodos reprodutivo e não-reprodutivo. Os valores de δ^{13}C e δ^{15}N de MB significativamente diferentes, sendo maiores para MB em relação a RFB, resultando em uma marcada partição de nicho entre as espécies ao longo de seus ciclos reprodutivo anuais. Adicionalmente, RFB variou amplitude de seu nicho de acordo com os períodos reprodutivos e não-reprodutivos de MB, que representam períodos de maior e menor intensidade de uso de recursos, respectivamente. Por fim, foram testadas variações sexuais nas estratégias de forrageio de MB tanto no período reprodutivo como não-reprodutivo, mas estas foram pouco significativas. A constante partição de nicho entre períodos e anos entre as espécies aparenta ter um papel essencial para a sua coexistência no arquipélago, além de sugerir que RFB ajusta seu período reprodutivo de acordo com o período não-reprodutivo de MB, quando a competição potencial por recursos é menos intensa. Mesmo sendo consideradas oásis em um ambiente oligotrófico, ilhas oceânicas impõem condições limitantes para espécies que dependem dos mesmos recursos e, portanto, são ótimos locais para ilustrar a partição de nicho entre espécies simpátricas. Isso revela informações sobre como essas espécies interagem no espaço e no tempo e como esses processos influenciam na manutenção da biodiversidade em regiões marinhas tropicais.

Palavras-chave: *biologging*, isótopos estáveis, oceanos tropicais, partição de nicho, relaxamento ecológico.

ABSTRACT

Tropical oceans are typically oligotrophic environments, with resources patchily distributed in space and time. This irregularity of prey availability makes adaptations in foraging strategies and niche partitioning essential for the survival of predators such as seabirds. This group tends to breed in multi-species colonies and exploit resources around the colony, especially during the breeding season. Breeding is a period of intense exploitation of resources to supply the energy requirements of parents and offspring. Thus, plastic foraging behavior allows seabirds to adapt to spatio-temporal variation at intra- and interspecific levels. In this context, this study aimed to characterize the foraging strategies of seabirds of the genus *Sula* in the Fernando de Noronha archipelago in intra- and interspecific levels, using biologging data and stable isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N) obtained between 2015 and 2022. For the masked booby (*Sula dactylatra*, MB), an inter-annual pattern of foraging areas was observed to the east of the archipelago, potentially associated with the interaction of currents with the topography, which generate a flow of ascending currents in this region. However, in 2022 the foraging area was reduced and concentrated close to the archipelago compared to previous years. Additionally, there was no isotopic niche overlap between that year and the others, and the proportion of prey contribution to the diet changed. This inter-annual variation may result from local oceanographic factors or the distribution of pelagic predators with which seabirds associate when foraging. These results demonstrate the trophic plasticity of MBs in adapting their foraging ranges to inter-annual variations in a tropical environment, highlighting their potential as monitors of variation in the distribution and composition of epipelagic fish. Subsequently, isotopic niche variations were tested between MB and red-footed booby (*Sula sula*, RFB) during breeding and non-breeding periods. The δ^{13}C and δ^{15}N values of MB were significantly different, being higher for MB compared to RFB, resulting in marked niche partitioning between the species throughout their annual breeding cycles. Furthermore, RFB varied the amplitude of its niche according to the breeding and non-breeding periods of MB, which represent periods of higher and lower intensity of resource use, respectively. Finally, sexual variations in the foraging strategies of MB were tested in both breeding and non-breeding periods but these were not significant. The consistent niche partitioning between periods and years among species appears to play an essential role in their coexistence in the archipelago, as well as suggesting that RFB adapts its reproductive period to the non-breeding period of MB, when potential resources competition is less intense. Although they are considered oases in an oligotrophic environment, oceanic islands impose limiting conditions on species that depend on the same resources and therefore, are ideal sites for illustrating niche partitioning among sympatric species. This revels information on how these species interact in space and time, and how these processes influence the maintenance of biodiversity in tropical marine regions.

Keywords: biologging, ecological release, niche partitioning, stable isotopes, tropical oceans.

1. INTRODUÇÃO GERAL

Oceanos tropicais são tipicamente oligotróficos e apresentam uma distribuição de recursos distribuídos de forma efêmera e irregular, podendo ainda ser influenciados pela sazonalidade, processos oceanográficos e fenômenos climáticos (Longhurst & Pauly 1987). A combinação desses fatores pode influenciar todos os níveis de teias tróficas marinhas, fazendo com que adaptações nas estratégias de forrageio e partição de recursos sejam essenciais para a sobrevivência de predadores (Montevecchi et al. 2009, Jessopp et al. 2020, Watanuki et al. 2022). Nesse sentido, observar as estratégias de forrageio desses organismos, ou seja, o conjunto de comportamentos, processos e adaptações que utilizam para localizar, selecionar e obter recursos alimentares (Stephens et al. 2007, Vogel et al. 2017), pode ser uma ferramenta para compreender a distribuição diferencial desses recursos no tempo e no espaço. Além disso, essas estratégias também permitem investigar como os recursos são partilhados entre predadores em ambientes oligotróficos, como oceanos tropicais (Tompkins et al. 2017, Cerveira et al. 2020, Fayet et al. 2023).

Aves marinhas são predadores que dependem inteiramente dos oceanos ao menos em uma parte de suas vidas (Votier & Sherley 2017) e que se reproduzem em colônias multiespecíficas (Schreiber & Burger 2001). Durante a reprodução, especialmente durante o período de cuidado com o filhote, aves marinhas utilizam recursos no entorno da colônia, retornando ao ninho periodicamente entre viagens de forrageio (*i.e.*, *central-place foragers*) (Schreiber & Burger 2001). Além disso, esse período demanda uma intensa exploração de recursos por parte das aves para provisionamento próprio e do filhote (Jessopp et al. 2020, Piña-Ortiz et al. 2024) e, desta forma, aves marinhas podem exibir estratégias de forrageio flexíveis, adaptando-se às variações espaço-temporais na disponibilidade de recursos para suprir esses requerimentos (Sommerfeld et al. 2015, Castillo-Guerrero et al. 2016, Piña-Ortiz et al. 2024). Nesse sentido, essa plasticidade de estratégias de forrageio contribui para que aves marinhas sejam consideradas bons organismos-modelo para estudos em oceanos tropicais, pois podem atuar como sentinelas de variações na disponibilidade de recursos no espaço e no tempo (Cairns 1987, Cherel & Weimerskirch 1999, Garthe et al. 2011).

A reprodução colonial também é um fator que potencialmente influencia no comportamento de forrageio, especialmente frente à coexistência de espécies com requerimentos ecológicos similares. Nesse sentido, a partição de nicho é uma alternativa à dependência por recursos semelhantes, de modo que haja o ajuste de uma ou mais dimensões dos nichos n-dimensionais das espécies (Hutchinson 1957, Schoener 1974). Em aves marinhas, diferentes estratégias foram desenvolvidas a fim de evitar a competição de recursos, como a segregação de áreas de forrageio e profundidade de mergulho, e no consumo de diferentes tipos de presas (Kappes et al. 2011, Barger et al. 2016, Almeida et al. 2021, Fayet et al. 2023). Além disso, fatores morfológicos como massa e tamanho corporal podem potencialmente contribuir para o desenvolvimento dessas estratégis distintas, tanto em nível inter como intraespecífico (Lewis et al. 2005, Catry et al. 2009, Mancini & Bugoni 2014). Complementarmente, a partição de nicho também pode variar de forma temporal, de modo que as espécies adaptem suas estratégias de forrageio de acordo com períodos de maior e menor intensidade do uso de recursos, relacionando-se com o conceito de relaxamento ecológico (Herrmann et al. 2021). Por exemplo, ao contrário do período reprodutivo, quando as aves necessitam suprir as suas demandas energéticas e as filhote, o período não-reprodutivo permite um comportamento de forrageio mais disperso e um uso de recursos menos intenso (Lisnizer & Yorio 2019, Mills et al. 2021, Roy et al. 2021). Dessa forma, para espécies que permanecem na colônia durante todo seu ciclo anual, alternar seus períodos reprodutivos pode ser uma alternativa para evitar a competição em períodos de maior estresse e promover sua coexistência.

O gênero *Sula* (Suliformes: Sulidae) engloba seis espécies, as quais apresentam distribuição tropical e temperada em todas as bacias oceânicas e que comumente formam colônias multiespecíficas (Nelson 1978). No arquipélago de Fernando de Noronha, o atobá-mascarado *Sula dactylatra* Lesson, 1831 e o atobá-de-pé-vermelho *Sula sula* (Linnaeus, 1766), ocorrem simpatricamente com outras nove espécies de aves marinhas (Mancini et al. 2016) e se reproduzem o ano todo, embora atobá-mascarado apresente picos reprodutivos entre fevereiro e maio e o atobá-de-pé-vermelho entre julho e outubro (Serafini et al. 2024). Atobás-mascarados são maiores em tamanho e massa corporal em relação aos atobás-de-pé-vermelho (Nelson 1978, Young et al. 2010) e ambas as espécies apresentam dimorfismo sexual reverso, com fêmeas maiores que os machos (Nelson 1978, Lewis et al. 2005). Em relação às estratégias de forrageio, estudos com essas espécies relatam que atobás-mascarados tendem a forragear mais próximos à colônia e tem peixes-voadores (Exocoetidae) como sua principal presa, enquanto atobás-de-pé-vermelho tendem a forragear em ambientes mais distantes da colônia e se alimentar de uma maior proporção de lulas (Young et al. 2010, Kappes et al. 2011, Almeida et al. 2021). Em Fernando de Noronha, peixes-voadores demonstram ser importantes fontes alimentares para aves marinhas (Mancini et al. 2014, Santos et al. 2019, Jacoby et al. 2023). Entretanto, essas espécies, assim como zooplâncton e outros peixes, podem apresentar uma distribuição espacial irregular no entorno do arquipélago, resultado das ressurgências de correntes à leste (Salvetat et al. 2022). Nesse contexto, a coexistência de atobás que dependem de recursos similares que estão distribuídos de forma irregular no entorno do arquipélago, permitem estudos acerca variações temporais na disponibilidade de recursos e também de interações tróficas durante períodos de alta demanda energética.

Estudos focados na distribuição espacial do forrageio e no uso de recursos estão tipicamente conectados e fornecem informações sobre diferentes e complementares dimensões do nicho ecológico (Garvey & Whiles 2016). A análise de isótopos estáveis é uma técnica amplamente utilizada em estudos com aves marinhas, pois permite a inferência de relações tróficas intra e interespecíficas no espaço e no tempo (Dalerum & Angerbjörn 2005, Fry 2006). Em estudos ecológicos marinhos, razões isotópicas de carbono (δ^{13}C) são utilizadas para identificar a origem costeira ou pelágica de presas ingeridas (Cherel & Hobson 2007, Mancini & Bugoni 2014), enquanto razões isotópicas de nitrogênio (δ^{15}N) atuam como marcadores de posição trófica (Hobson et al. 1994, Fry 2006). Dessa forma, ao utilizar valores de δ^{13}C e δ^{15}N como coordenadas bidimensionais, o espaço-δ resultante representa o nicho isotópico, um *proxy* para nicho trófico (Newsome et al. 2007, Jackson et al. 2011). De forma complementar, técnicas de rastreamento remoto (*i.e.*, *biologging*) permitem a observação remota de movimento, permitindo a identificação de diferentes comportamentos através de análise de trajetórias (Patterson et al. 2009). Além disso, a associação de diferentes dispositivos (*e.g.*, receptores de sinal de GPS, sensores de pressão) podem contribuir para refinar a interpretação de estratégias de uso do espaço (Wilmers et al. 2015, Roy et al. 2022), e por isso tem sido aplicada amplamente em estudos com aves marinhas (Austin et al. 2021, Fromant et al. 2022, Fayet et al. 2023). Portanto, a associação de técnicas de rastreamento remoto e isótopos estáveis promovem informações tanto de estratégias de forrageio de organismos, como também permitem identificar suas variações intra e interespecíficas no espaço e no tempo.

Nesse contexto, o presente trabalho procurou caracterizar as estratégias de forrageio no tempo e no espaço de aves marinhas do gênero *Sula* no arquipélago de Fernando de Noronha em nível intra e interespecífico utilizando dados de rastreamento remoto e isótopos estáveis obtidos sistematicamente entre 2015 e 2022. Primeiramente, os dados obtidos das duas técnicas foram utilizados para testar diferenças interanuais no uso do espaço e de recursos alimentares por *S. dactylatra* durante seu período reprodutivo. Nesse contexto, considerando fatores oceanográficos que promovem a concentração de presas potenciais à leste do arquipélago, não são esperadas variações interanuais significativas nas estratégias de forrageio da espécie. Além disso, dados de isótopos estáveis também foram utilizados para testar diferenças na dieta entre *S. dactylatra* e *S. sula* durante seus períodos reprodutivo e não-reprodutivo sendo esperada uma segregação de nicho trófico entre as duas espécies, considerando suas características morfológicas e comportamentais.

2. ESTRUTURA DA DISSERTAÇÃO

A presente dissertação está organizada em dois capítulos. O capítulo 1 aborda variações interanuais nas estratégias de forrageio de *S. dactylatra* em período reprodutivo, relacionando-as com processos oceanográficos no entorno da colônia. O capítulo 2 retrata variações interespecíficas nas estratégias de forrageio de *S. dactylatra* e *S. sula* durante o período reprodutivo e não-reprodutivo de cada uma das espécies. Parte dos dados foi fornecida pelo *Institut de recherche pour le développement*, e parte foi obtida após receber a Autorização SISBIO 64234, e parecer favorável da CEUA/UFRGS nº 37905, ambos documentos incluídos como anexos nesta dissertação. Adicionalmente, as amostras obtidas e utilizadas foram cadastradas no Sistema Nacional de Gestão do Patrimônio Genético e do Conhecimento Tradicional Associado (comprovante de cadastro anexo).

3. CAPÍTULO 1 - Flexible foraging strategies of a tropical seabird in the western Atlantic Ocean

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Flexible foraging strategies of a tropical seabird in the western Atlantic Ocean

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ABSTRACT: Tropical oceans are typically oligotrophic but they can feature productive environments, such as islands, which can promote high prey availability and, consequently, influence predators' foraging strategies in time and space. This study investigates interannual and sex-specific variations in the foraging ecology of the masked booby (*Sula dactylatra*) in the Fernando de Noronha Archipelago (FdN), western tropical Atlantic Ocean. During four breeding seasons, blood from birds and muscle samples from regurgitated prey were collected for stable isotope analysis of carbon (δ^{13}C) and nitrogen (δ^{15}N). Simultaneously, birds were tracked with GPS devices, and their dives, both recorded and predicted by a U-shaped deep neural network, were used to estimate foraging areas. Significant variations in δ^{13}C and δ^{15}N values occurred over the four years, and all isotopic niches overlapped, except from 2022. Stable isotope variations between sexes were occasional, with overlapping niches across all years. Mixing models estimated *H. affinis* as the main prey source from 2017 to 2019, shifting to *P. gibbifrons* and *C. cyanopterus* in 2022. Tracking data revealed that foraging areas were located eastward of the archipelago in all years, potentially driven by the Island Mass Effect on prey distribution. Foraging areas were closer to the archipelago in 2022, with shorter duration and length of foraging trips. These findings showcase potential predictability in foraging areas, but also their interannual variability, suggesting shifts in prey availability and distribution around FdN. This highlights the ecological plasticity of masked boobies in tropical environments and their potential as monitors of fish community dynamics.

KEY WORDS: biologging, deep learning, Island Mass Effect, stable isotopes, *Sula dactylatra*, trophic ecology, tropical oceans

1. INTRODUCTION

Oligotrophic tropical oceans exhibit unpredictable and patchy resources and can be influenced, even to a lesser extent than temperate and polar oceans, by seasonality, oceanographic dynamics, and climate oscillations (Longhurst & Pauly 1987). These factors pose challenges to the different levels of the trophic web, such as top predators, which need to locate food efficiently and adapt to potential variations in its availability (Link 2004, Watanuki et al. 2022), including those associated with present and future climate change scenarios (Kwiatkowski et al. 2017, McDuie et al. 2018). Notwithstanding, productive environments in tropical oceans, such as islands, seamounts, and upwellings, can provide areas of high food resource availability (Zavalaga et al. 2010, Wilkinson et al. 2020), such as small pelagic fish, which plays a critical ecosystemic role in the energy transfer between basal and top trophic levels (Cairns 1987, Montevecchi & Myers 1996). Therefore, the distribution and availability of mid-level prey directly influence the foraging of top predators, such as large fish, marine mammals, and seabirds, which can potentially act as indicators of prey distribution in time and space (Link 2004, Staniland et al. 2006, Spitz et al. 2011, Cherel 2020).

The western tropical Atlantic Ocean features topographic characteristics that create biomass and productivity hotspots, a process known as the Island Mass Effect (Doty & Oguri 1956, Gove et al. 2016). The interaction of the South Equatorial Current (SEAc), the South Equatorial Undercurrent (SEUC), and the Equatorial Undercurrent (EUC) with the archipelagos of São Pedro and São Paulo, Fernando de Noronha, and Rocas Atoll generates eddies and turbulence (Araujo & Cintra 2009). These hydrodynamic processes typically contribute to making these areas highly biodiverse and productive (Araujo & Cintra 2009, Tchamabi et al. 2017). Fernando de Noronha exhibits complex trophic webs in different water column strata (Eduardo et al. 2023), and organisms such as fish and zooplankton are irregularly distributed around the archipelago, as a result of ascending waters eastward (Costa da Silva et al. 2021, Salvetat et al. 2022). Flying fish (Exocoetidae) are important food resources for top predators around Fernando de Noronha, such as yellowfin tuna (*Thunnus albacares*), dolphinfish (*Coryphaena hippurus*) (Martins et al. 2021), and seabirds like tropicbirds (*Phaethon* spp.) and boobies (*Sula* spp.) (Mancini et al. 2013, Santos et al. 2019, Jacoby et al. 2023). However, little is known about the availability and distribution of these epipelagic fish in the archipelago, and they may be associated with small and medium-scale oceanographic processes, as well as their possible temporal and spatial variations.

Seabirds typically nest on coastal and oceanic islands and exploit resources around their colonies during the breeding season, acting as central place foragers (Schreiber & Burger 2002). Thus, seabirds can exhibit flexible foraging strategies that allow them to explore a wide range of prey, and adapt to spatiotemporal variations in their foraging areas (Sommerfeld et al. 2015, Castillo-Guerrero et al. 2016, Cerveira et al. 2020). Boobies (Suliformes: Sulidae) are seabirds distributed in subtropical and tropical regions, have reverse sexual dimorphism (i.e., females are larger and heavier than males), and their diet is based primarily on flying fish and squid (Nelson 1978). Boobies demonstrate flexible foraging behaviors in response to spatial and temporal variations in prey availability and distribution around their colonies, which can be investigated through their movements (Weimerskirch et al. 2008, Sommerfeld et al. 2015, Soanes et al. 2021) and diet (Castillo-Guerrero et al. 2016, Donahue et al. 2020). Consequently, booby foraging strategies are potentially shaped by the conditions around their colonies (Jacoby et al. 2023), unraveling local trophic relationships and their potential variations in space and time.

Studies focusing on foraging distribution and food resource use are typically interconnected and provide information on complementary dimensions of the ecological niche (Garvey & Whiles 2016). Biologging techniques enable remote observation of animal movements, allowing the identification of different behaviors through trajectory analysis (Patterson et al. 2009). Consequently, this information allows the characterization of space use strategies (Wilmers et al. 2015, Roy et al. 2022), which has been widely employed in seabird studies (Machovsky-Capuska et al. 2016, Austin et al. 2021). Complementarily, stable isotope analysis allows the inference of trophic interactions through isotopic ratios. In ecological studies, the carbon isotopic ratio (δ^{13}C) is used as an indicator of foraging habitat, such as inshore/offshore areas (Cherel & Hobson 2007), while the nitrogen isotopic ratio (δ^{15}N) provides information about the trophic level of predators (Fry 2006). Thus, δ^{13}C and δ^{15}N are considered two dimensions of the ecological niche – or isotopic niche (Newsome et al. 2007, Jackson et al. 2011) – and allow for testing spatiotemporal intraspecific variations in food resources (Dalerum & Angerbjörn 2005), as well as proportions of prey assimilated from distinct biological tissues (Parnell et al. 2013). Therefore, combining biologging and stable isotopes can provide complementary information on foraging strategies and their variations through time and space, shedding light on the ability to adapt to environmental conditions around colonies.

Fernando de Noronha is the archipelago with the greatest number of breeding seabird species in Brazil. Currently, only the white-tailed tropicbird *Phaethon lepturus* (Campos et al. 2018, Santos et al. 2019) and the masked booby *Sula dactylatra* have been tracked during the non-breeding (Roy et al. 2021) and breeding (Roy et al. 2022) seasons. In this context, the present study aims to characterize interannual variations in the foraging strategies of masked boobies around Fernando de Noronha, in the western tropical Atlantic Ocean, by combining movement and diet patterns during the breeding period. For this, we collected biologging data obtained during foraging trips around the colony, stable isotopes of carbon and nitrogen from birds and their prey over four breeding seasons. Given the scenario of increased food availability around Fernando de Noronha due to small and medium-scale oceanographic processes resulting from the interaction of ocean currents with the bottom topography, we expect that masked boobies do not present interannual variations in foraging strategies, as the spatial distribution of prey becomes more predictable under such conditions.

2. MATERIALS & METHODS

2.1 Study area

The study was carried out on Meio Island (3°49'11.6" S; 32°23'35.362" W), a secondary islet belonging to the Fernando de Noronha Archipelago, located 360 km off the Brazilian coast (Fig. 1). The archipelago experiences two well-defined seasons, a rainy season from March to July and a dry season from August to January (Serafini et al. 2010), but these do not imply significant environmental variations in the surrounding surface waters (Salvetat et al. 2022). Meio Island covers approximately 0.16 km^2, most of which is covered by herbaceous vegetation and exposed soil, where masked colonies occur (Gaiotto et al. 2022). The breeding population size in Meio Island was estimated at 181, 388, and 162 breeding pairs respectively in 2017, 2018, and 2019 based on ground counts of incubating individuals and emancipated chicks. Between 2017 and 2018, black rats (*Rattus rattus*) were eradicated from the island in order to favor the reproductive success of boobies as predation on eggs and chicks was common.

2.2 Sampling methods

Sampling was carried out in 2017, 2018, 2019, and 2022 during the chick-rearing period (March–April) of masked boobies (Serafini et al. 2024). Breeding individuals who brooded chicks at an early stage of development were captured manually or with a nylon snare on the end of a fishing rod. Females and males were identified through vocalization (Nelson 1978). A GPS tracking device (igotU GT-120, Mobile Action, Taiwan; or Axy-Trek Marine, TechnoSmart, Italy) was attached to the central tail feathers of each individual using TESA® tape, without exceeding 3% of the bird body mass (Phillips et al. 2003). Loggers were set to record a position every 10–15 s. The IgotU model devices only provided position information, while the Axy-Trek devices also featured pressure sensors. From these, the pressure was measured for 55 individuals, enabling the identification of diving bouts. After two to three days, birds were recaptured for logger retrieval and biological sampling. Blood samples (0.3 mL) were collected from the metatarsal vein using sterile syringes/needles and stored in microtubes. During bird handling, spontaneous regurgitations of undigested material were collected, stored in plastic bags, and frozen at -20 °C. Subsequently, prey items were identified at the lowest possible taxonomic level, measured using a stop ruler, and muscle samples were collected and stored in microtubes with 70% ethanol.

2.3 Stable isotope analysis

Prey samples were washed in a Soxhlet extractor for a 6 h cycle using a 2:1 chloroform:methanol solution as a solvent to remove lipids (Logan et al. 2008, Nunes et al. 2018). Lipids from blood samples were not extracted as they were present in low concentrations (Bearhop et al. 2002). Subsequently, all muscle and blood samples were lyophilized, grounded, and homogenized, and subsamples of ~0.7 mg were placed in tin capsules for stable isotope analysis (SIA) of carbon (δ^{13}C) and nitrogen (δ^{15}N) using an isotope ratio mass spectrometer at the *Pôle Spectrométrie Océan* of the *Institut Universitaire Européen de la Mer* (PSO-IUEM, France), and the *Centro Integrado de Análises* of the *Universidade Federal do Rio Grande* (CIA-FURG, Brazil). Differences between sample and standard ratios (Vienna Pee Dee Belemnite for δ^{13}C; atmospheric air for δ^{15}N) are expressed in δ notation in parts per thousand (‰). The accuracy of the measurements was checked by repeated analyses of internal samples of acetanilide at the PSO-IUEM and glutamic acid and caffeine at the CIA-FURG.

The mean and standard deviation of isotopic values between years were calculated using the FSA package (Ogle et al. 2023) in the R software (R Core Team 2024). Subsequently, univariate differences between sexes and years were tested using the Kruskal-Wallis test and the Mann-Whitney U test as a post-hoc test, using False Discovery Rate for p-value adjustment (Benjamini & Hochberg 1995). Considering the reversed sexual size dimorphism of the species, the same tests were conducted between sexes in each year and for each sex throughout the years. Additionally, the isotopic niches of females and males per year were estimated using a Bayesian approach implemented in the SIBER package (Jackson et al. 2011). Finally, the contribution of each prey species to the diet of females and males was estimated with Bayesian mixing models in the simmr package (Govan & Parnell 2023). The discriminant factors used in the mixing models were -0.18 ± 0.1‰ for δ^{13}C and 1.72 ± 0.1‰ for δ^{15}N, estimated for the Atlantic puffin *Fratercula arctica* (Jenkins et al. 2020). The prey species used in the models were *Cheilopogon cyanopterus*, *Hirundichthys affinis, Oxyporhamphus micropterus, Prognichthys gibbifrons,* and *Exocoetus volitans* and were chosen based on the main species of fish found in regurgitates from handled masked boobies, collected in all sampled years (author’s unpubl. data). The latter species was separated into intermediate (int, 100–150 mm) and large (lg, >150 mm) size classes due to the potential importance of this species for the diet (Nunes et al. 2018), and the differentiation of isotopic values between size classes (Govan & Parnell 2023).

2.4 Biologging analysis

Bird trajectories were split into distinct central-place foraging trips. Dive occurrences were detected from pressure sensors, specifically in situations where the estimated depth was below 1 m, given natural variations of the equipment records and atmospheric pressure. The trajectories of individuals who did not have pressure sensors were segmented for the identification of dive bouts using a dedicated U-shaped deep neural network (Roy et al. 2022). This model allows to infer the diving behavior of seabirds solely based on the geometry of their flight paths. It was properly trained and validated leading to above 91% predictive accuracy on test trajectories of datasets that were not used in the training or validation process. Finally, the observed and predicted dive occurrences were used to estimate potential foraging areas using Kernel Density Estimation (KDE). We evaluated the similarity between pairs of these foraging maps using two metrics: the root mean squared error (RMSE) (Wilson 2011) as well as the Bhattacharyya coefficient (BC) (Winner et al. 2018).

Additionally, for complete trips (i.e., first and last points recorded at the colony) of males and females, the following metrics were calculated: total distance traveled (D_{tot}, km), maximum distance from the colony (D_{max}, km), trip duration (T_{dur}, min), proportion of time (min) diving (P_{div}, %), and straightness index SI, ratio ranging from 0 to 1. The straightness index of a central-place foraging trajectory was defined as two times the quotient between the D_{max} and D_{tot} (Benhamou 2004). For each metric, univariate differences between sexes per year were tested using the Mann-Whitney U test, with False Discovery Rate used for p-value adjustment (Benjamini & Hochberg 1995). Additionally, to analyze pairwise differences of each metric between years, a *t*-test was carried out considering data from males and females together.

3. RESULTS

3.1 Stable isotopes

Ninety-seven blood samples from masked boobies were analyzed, 43 from females and 54 from males (Table 1). The mean and standard deviation for δ^{13}C ranged from -17.62 ± 0.04‰ (2022) to -16.58 ± 0.10‰ (2017) for females, and from -17.66 ± 0.11‰ (2022) to -16.61 ± 0.08‰ (2017) for males. For δ^{15}N, values varied from 10.50 ± 0.24‰ (2017) to 11.02 ± 0.18‰ (2022) for females, and from 10.34 ± 0.18‰ (2017) to 10.80 ± 0.09‰ (2019) for males (Table 1). Additionally, a total of 61 prey samples were analyzed (Table 2). The δ^{13}C values varied from -17.81 ± 0.26‰ (*C. cyanopterus*) to -17.09 ± 0.40‰ (*E. volitans* int), and δ^{15}N values ranged from 7.66 ± 1.44‰ (*O. micropterus*) to 10.29 ± 0.02‰ (*P. gibbifrons*) (Table 2).

Considering all samples, significant differences were found between years for δ^{13}C (Kruskall-Wallis, chi-squared = 78.64, $p < 0.01$) and δ^{15}N (Kruskall-Wallis, chi-squared = 42.11, $p < 0.01$). Paired differences were significant between all years ($p < 0.01$), except between 2017 and 2019 for δ^{13}C (Mann-Whitney, $p = 0.09$), and between 2019 and 2022 for δ^{15}N (Mann-Whitney, $p = 0.61$). Regarding intersexual variations per year, no significant differences were identified for δ^{13}C ($p > 0.05$), and for δ^{15}N there were significant differences in 2017 (chi-squared = 4.43, $p < 0.05$), 2018 (chi-squared = 11.454, $p < 0.01$) and 2022 (chi-squared = 8.5283, $p < 0.01$) (Fig. 2). Additionally, paired differences for females were significant between all years for δ^{13}C ($p < 0.01$), except between 2017 vs. 2019 ($p = 0.6$), and for δ^{15}N were significant only between 2017 vs. 2019, 2017 vs. 2022, and 2018 vs. 2022 ($p < 0.01$). Paired differences for males were significant between all years for δ^{13}C ($p < 0.01$) and for δ^{15}N ($p \leq 0.05$), except between 2019 vs. 2022 ($p = 0.44$). The only year with no isotopic niche overlap with previous years for both sexes was 2022 (Fig. 3a). Moreover, a partial overlap between males and females was observed in all years (Fig. 3b, Table S1), with males having a narrower niche than females. However, this pattern was reversed in 2022 when males presented a wider niche compared to females and also with male niches from previous years (Fig. 3b, Table S1).

Mixing models demonstrated annual variations in the contribution of each prey to the diet of males and females. In 2017, 2018, and 2019, *H. affinis* was the most important prey source for both sexes (from 21.5% to 42.9%). In 2022, its contribution decreased to 16.9% for females and 15.4% for males (Table 3, Fig. 4), and there was an increase in importance for *P. gibbifrons* and *C. cyanopterus*, representing the two prey items with the highest contributions to the diet of both sexes (up to 27.0% for *P. gibbifrons* and up to 20.4% for *C. cyanopterus*) (Table 3, Fig. 4).

3.2 Foraging areas

In total, 88 birds were tracked, 42 females and 46 males, and 235 complete foraging trips were recorded, 116 from females and 119 from males (Table 4). The mean D_{tot} (in km) ranged from 104.2 ± 46.8 (2022) to 170.4 ± 119.5 (2018) for females and from 101.3 ± 50.2 (2022) to 198.0 ± 147.2 (2019) for males. The D_{max} (in km) had the lowest averages in 2022 for females and males (38.8 ± 18.4 and 37.3 ± 19.4, respectively) and the highest in 2018 for females (65.9 ± 51.6) and in 2019 for males (59.8 ± 39.9). T_{dur} (in min) means ranged from 241.9 ± 121.4 (2022) to 512.6 ± 439.3 (2019) for females and 242.4 ± 131.9 (2022) to 594.8 ± 693.2 (2018) for males. The P_{div} varied from 0.010% (2019) to 0.015% (2017) for females and from 0.013% (2019) to 0.020% (2018) for males (Table 4). The values of D_{tot}, D_{max}, and T_{dur} were significantly lower in 2022 compared with previous years for males and females together (*t*-test, $p < 0.01$) (Fig. 5). The P_{div} differed significantly between 2017 vs. 2019, 2018 vs. 2019, and 2019 vs. 2022 (*t*-test, $p < 0.05$). Additionally, the SI index only differed significantly between 2022 vs. 2018 and 2022 vs. 2019 (Fig. 5). Differences between males and females were not significant for any of the analyzed trip metrics (Mann-Whitney, $p > 0.05$) (Fig. 6). Regarding foraging areas, it was observed that boobies mostly explored regions eastward of Meio Island in all years (Fig. 7). However, variations in the size and extent of foraging areas were especially relevant in 2022, when the birds foraged nearer the colony (Fig. 7). For both males and females, the smallest overlaps (i.e., the highest dissimilarities) in foraging areas were observed between 2022 vs. 2019, followed by 2022 vs. 2018, considering the Bhattacharyya coefficient, and between 2022 and the remaining years when considering the root mean square deviation (Fig. 8).

4. DISCUSSION

This study revealed interannual consistency in the location of foraging areas of masked boobies breeding at Fernando de Noronha. Nevertheless, we found interannual variation in their foraging strategies, especially in 2022, when the foraging areas were situated nearer to the colony with an associated change in diet composition. This suggests that the foraging strategies of masked boobies may be shaped by the species-specific prey availability around the colony. Additionally, intersexual differences in foraging strategies were not substantial, with low spatial and isotopic niche segregation, even though females showed higher nitrogen values than males.

The interannual stability of foraging areas east of Fernando de Noronha may be linked with the spatial distribution of prey, which could be related to the oceanographic dynamics around the archipelago. The Island Mass Effect predicts that primary productivity is concentrated leeward, due to windward disturbances (Doty & Oguri 1956).

This phenomenon occurs in Fernando de Noronha, where the ocean circulation interacts with the island topography on the east side, ascending vertically, resulting in higher primary productivity and zooplankton concentration to the west (Tchamabi et al. 2017, Salvetat et al. 2022). However, the flow of particles and zooplankton generated by upwellings to the east (i.e., leeward) is an essential energy source for planktivorous fish, leading to increased secondary production eastward (Salvetat et al. 2022). Thus, the Island Mass Effect can promote a certain predictability of areas with abundant resources, which can lead to a fidelity of foraging sites over the years. This pattern is not expected as a rule for tropical seabirds (Weimerskirch 2007), although it has also been identified in Peruvian boobies *S. variegata* in the highly productive Humboldt Current System along the Peruvian coast (Zavalaga et al. 2010), and in masked boobies in Pedro Bank, Jamaica, associated with a local bathymetric feature (Wilkinson et al. 2020). Additionally, the stability of the foraging area between years may also result from the stable distribution of epipelagic fish assemblages and large pelagic predators, such as tunas and sharks (Salvetat et al. 2022). Most tropical birds associate with these subsurface predators, which concentrate the fish at the sea surface from below making it available for seabirds (Balance & Pitman 1999, Miller et al. 2018). Thus, masked boobies would benefit from the predictability of areas with abundant prey, promoted by subsurface pelagic predators. Finally, both of these potential explanations could also give an advantage to these seabirds, which are known to use social information to locate their prey (Thiebault et al. 2014, Boyd et al. 2016).

Interannual variations in foraging strategies can be associated with the plastic behavior of boobies, which can reflect the changes in prey composition and distribution around the colony. Seabirds with flexible foraging behavior can adapt to shifts in prey availability (Montevecchi et al. 2009, Garthe et al. 2011), and during the chick-rearing period they face higher time and distance constraints on their foraging trips due to the demand from nest attendance (Weimerskirch et al. 1997). In 2022, the isotopic niche of masked boobies did not overlap with those from previous years, and simultaneously, foraging areas were concentrated nearer the colony. This coincided with an increase in the proportion of *P. gibbifrons* and *C. cyanopterus* in the diet and a consequent decrease in the importance of *H. affinis* importance. Additionally, the time spent foraging, total and maximal distances of foraging trips, were significantly lower in 2022 compared with previous years, and the overlap between foraging areas observed in 2022 and in the remaining years was the lowest. Such variations may indicate that prey patches were nearer the archipelago in 2022 and exhibited variations in the occurrence of Exocoetidae species. This could be driven by changes in the ocean currents intensities that interact with the archipelago (Costa da Silva et al. 2021), which may potentially affect the complex trophic web associated with the ascending waters (Salvetat et al. 2022, Eduardo et al. 2022) and therefore, prey distribution and availability. However, the spatial distribution of flying fish schools is very difficult to predict (Oxenford et al. 1995), especially on the small spatial and temporal scales, limiting potential explanations related to oceanographic conditions. Alternatively, flying fishes are also pursued by pelagic predators such as sharks and tunas, with which seabirds associate to catch their prey (Balance & Pitman 1999, Weimerskirch et al. 2008). Thus, masked boobies could have explored areas with more accessible or abundant prey, leading to a reduction in foraging costs during the chick-rearing period, as observed in the masked booby in Australia (Sommerfeld et al. 2015) and other booby species in Peru (Zavalaga et al. 2007, 2010). Therefore, the availability of prey near the colony in 2022 could have triggered the switch to prey that could be captured during shorter trips, requiring less time and energy.

Understanding seabird foraging strategies requires studies at the intraspecific level, as responses to variations in environmental conditions can be sex-specific (Gissi et al. 2023). In Fernando de Noronha we found weak sexual segregation in isotopic niches and foraging areas as found for other species elsewhere (Young et al. 2010, Kappes et al. 2011, Mancini et al. 2013, Oppel et al. 2015, Poli et al. 2017, Soanes et al. 2021). This may be associated with the high availability of food resources around the archipelago. Although located in the typically oligotrophic tropical ocean, the colony surroundings are influenced by oceanographic processes which increase local productivity (Campelo et al. 2019) and thus can contribute to reducing sexual competition (Zavalaga et al. 2010). Additionally, the surrounding waters provide abundant resources for large pelagic predators including ten other breeding seabird species (Mancini et al. 2016), and the year-round presence of masked boobies in the colony (Roy et al. 2021). Despite being weak, the significant difference in nitrogen values between sexes may be related to factors not mutually exclusive, such as the larger body size and mass of females, that may allow exploring larger prey and higher trophic levels (Bearhop et al. 2006), but also to physiological peculiarities of females, considering specific demands of egg laying and chick rearing during the breeding period (Castillo-Guerrero et al. 2016, Lerma et al. 2020). Therefore, such findings suggest that a tropical archipelago with high food resource availability can contribute to reducing sexual competition, as predicted by fundamental theories of ecological niche and competitive exclusion (Hutchinson 1957).

The use of complementary techniques such as stable isotope analysis and biologging provides more reliable information concerning foraging strategies. However, the interpretations need caution considering the inherent limitations of the methods and also small sample sizes. Stable isotopes in marine environments are influenced by variations in baselines over time and space (Graham et al. 2010, Magozzi et al. 2017). In this sense, temporal variations in ocean circulation around the Fernando de Noronha

Archipelago can influence oceanographic parameters such as temperature (Costa da Silva et al. 2021), and productivity, which could potentially influence isotopic baselines (Graham et al. 2010). Also, the use of similar prey (i.e., flying fish), which share similar feeding habits (Collette et al. 2019), and variable sample sizes in the mixing models may bias the proportion of contribution to diet between years. However, with the integration of tracking data, it was possible to observe interannual differences in bird movements similar to those observed in isotopic data, such as the differences observed in 2022 compared to previous years. Therefore, the complementarity of the techniques used was essential for identifying patterns and temporal variations in the foraging strategies of the birds, reducing potential misinterpretations of the results.

In the present study, we identified an interannual persistence of areas with resource availability in a tropical archipelago through the foraging strategies of a seabird. Meanwhile, the interannual approach was also a key to identify temporal variations in the extent of foraging areas and species consumed. These findings reinforce the role of seabirds as important indicators of variations in the spatiotemporal distribution of the epipelagic fish community composition around colonies, as they respond to such variations through trophic plasticity. Furthermore, it is important to highlight the combination of complementary techniques, such as biologging and deep learning tools, which allow the identification of movement patterns in time and space, and stable isotopes, which provide information about ecological niches and prey assimilation. Islands surrounded by tropical oceans are considered oases in an oligotrophic environment (Gove et al. 2016) but may undergo changes in oceanographic conditions and, consequently, in the surrounding resources (Poli et al. 2017, McDuie et al. 2018). Local conditions around colonies are known to influence genetic structure in seabirds through differentiation by local adaptation (Nunes & Bugoni 2018, Muraro et al. 2024).

Thus, physical-chemical alterations in the ocean promoted by climate changes could influence prey distribution and composition, leading to potential changes in the observed seabird foraging strategies. In current and future scenarios associated with the impacts of climate change, using organisms that predominantly depend on a specific resource as samplers of a known marine region can provide rapid insights into the consequences of environmental changes through interannual sampling.

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TABLES

Table 1. Mean ± standard deviation (SD), minimum and maximum values of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic values from blood samples of females and males of masked boobies (*Sula dactylatra*) from Fernando de Noronha Archipelago, tropical western Atlantic Ocean, during breeding season through sampling years

	Female							**Male**						
	$\delta^{13}C$ (‰)				**$\delta^{15}N$ (‰)**			**$\delta^{13}C$ (‰)**				**$\delta^{15}N$ (‰)**		
	n	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**n**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**
2017	9	-16.58±0.10	-16.80	-16.43	10.50±0.24	10.05	10.84	21	-16.61±0.08	-16.73	-16.44	10.34±0.18	10.07	10.89
2018	21	-16.92± 0.16	-17.18	-16.55	10.71±0.26	10.28	11.40	13	-17.01±0.14	-17.30	-16.79	10.42±0.10	10.25	10.55
2019	7	-16.62±0.09	-16.75	-16.53	10.96±0.38	10.58	11.72	5	-16.72±0.06	-16.79	-16.64	10.80±0.09	10.72	10.96
2022	6	-17.62±0.04	-17.67	-17.55	11.02±0.18	10.81	11.28	15	-17.66±0.11	-17.91	-17.52	10.74±0.14	10.44	11.01

Table 2. Mean ± standard deviation (SD), minimum and maximum values of carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopic values from muscle samples of regurgitated prey of masked boobies (*Sula dactylatra*) from Fernando de Noronha archipelago. int: intermediate size (100–150 mm); lg: large size (> 150 mm)

		Length (mm)	**δ^{13}C (‰)**			**δ^{15}N (‰)**		
Prey species	**n**	**Mean**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**
Cheilopogon cyanopterus	4	250.0	-17.81 ± 0.26	-18.11	-17.57	9.75 ± 1.55	7.66	11.06
Exocoetus volitans (int)	5	129.0	-17.09 ± 0.40	-17.78	-16.76	8.45 ± 2.11	5.94	10.55
Exocoetus volitans (lg)	20	170.1	-17.29 ± 0.43	-18.29	-16.84	9.55 ± 1.02	5.90	10.48
Hirundichthys affinis	24	194.2	-17.13 ± 0.30	-17.60	-16.69	9.00 ± 0.83	7.90	10.90
Oxyporhamphus micropterus	6	132.5	-17.30 ± 0.49	-17.83	-16.63	7.66 ± 1.44	5.28	9.34
Prognichthys gibbifrons	2	212.5	-17.46 ± 0.21	-17.61	-17.32	10.29 ± 0.02	10.27	10.31

Table 3. Prey species proportions (%) of contribution to the diet of females and males of masked booby (*Sula dactylatra*) from Fernando de Noronha Archipelago during the breeding season estimated from mixing models of stable isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N), separated by sampling years. int: intermediate size (100–150 mm); lg: large size (>150 mm)

	Females				**Males**			
Prey species	**2017**	**2018**	**2019**	**2022**	**2017**	**2018**	**2019**	**2022**
Cheilopogon cyanopterus	10.2	5.8	12.2	17.2	5.9	6.4	13.2	20.4
Exocoetus volitans (int)	13.9	9.9	13.0	10.7	10.3	12.6	14.7	9.1
Exocoetus volitans (lg)	15.6	15.0	18.6	15.5	12.1	13.0	17.8	12.4
Hirundichthys affinis	28.3	42.9	23.0	16.9	38.8	39.8	21.5	15.4
Oxyporhamphus micropterus	19.5	13.8	13.6	12.7	24.1	19.3	15.6	18.5
Prognichthys gibbifrons	12.5	12.6	19.6	27.0	7.8	9.0	17.2	24.3

Table 4. Trip metrics (mean ± standard deviation) of females and males of masked booby (*Sula dactylatra*) tracked in the Fernando de Noronha Archipelago during the breeding season by year and the number of trips for each sex and year. N_b: total number of birds tracked; N_t: total number of complete trips recorded; D_{tot}: total distance traveled (km); D_{max}: maximum distance from the colony (km); T_{dur}: trip duration (min); P_{div}: proportion of time diving (%); SI: straightness index

	FEMALES							**MALES**						
	N_b	**N_t**	**D_{tot}**	**D_{max}**	**T_{dur}**	**P_{div}**	**SI**	**N_b**	**N_t**	**D_{tot}**	**D_{max}**	**T_{dur}**	**P_{div}**	**SI**
2017	10	20	154.3±78.9	61.3±31.1	335.0±239.2	0.015	0.8±0.1	18	29	163.7±100.1	56.5±35.4	437.4±428.9	0.016	0.7±0.2
2018	10	22	170.4±119.5	65.9±51.6	386.9±332.5	0.014	0.6±0.2	5	7	165.9±75.7	50.1±25.0	594.8±693.2	0.020	0.5±0.1
2019	7	24	162.2±95.6	60.2±49.5	512.6±439.3	0.010	0.7±0.2	5	18	198.0±147.2	59.8±39.9	585.1±723.1	0.013	0.6±0.2
2022	15	50	104.2±46.8	38.8±18.4	241.9±121.4	0.013	0.8±0.1	18	65	101.3±50.2	37.3±19.4	242.4±131.9	0.015	0.7±0.1

FIGURES

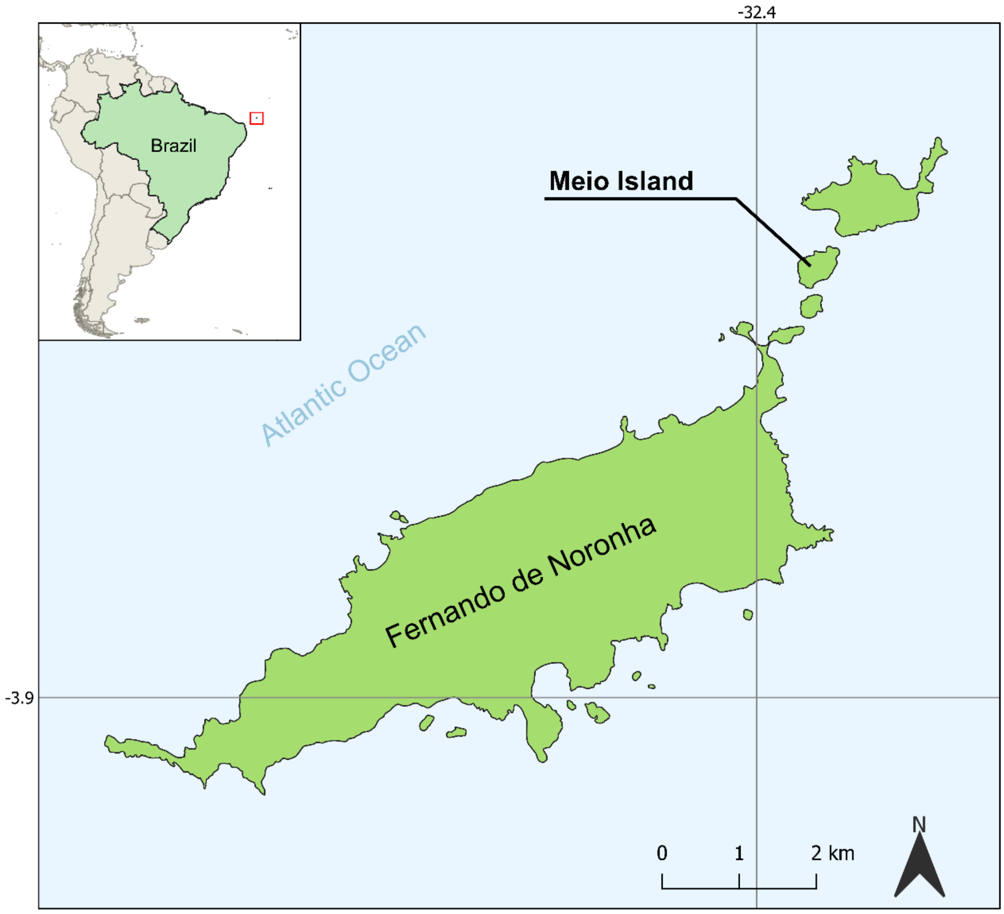

Fig. 1. Meio Island, Fernando de Noronha Archipelago, tropical Atlantic Ocean, where is located the main colony of masked booby (*Sula dactylatra*) sampled and tracked from 2017 to 2022

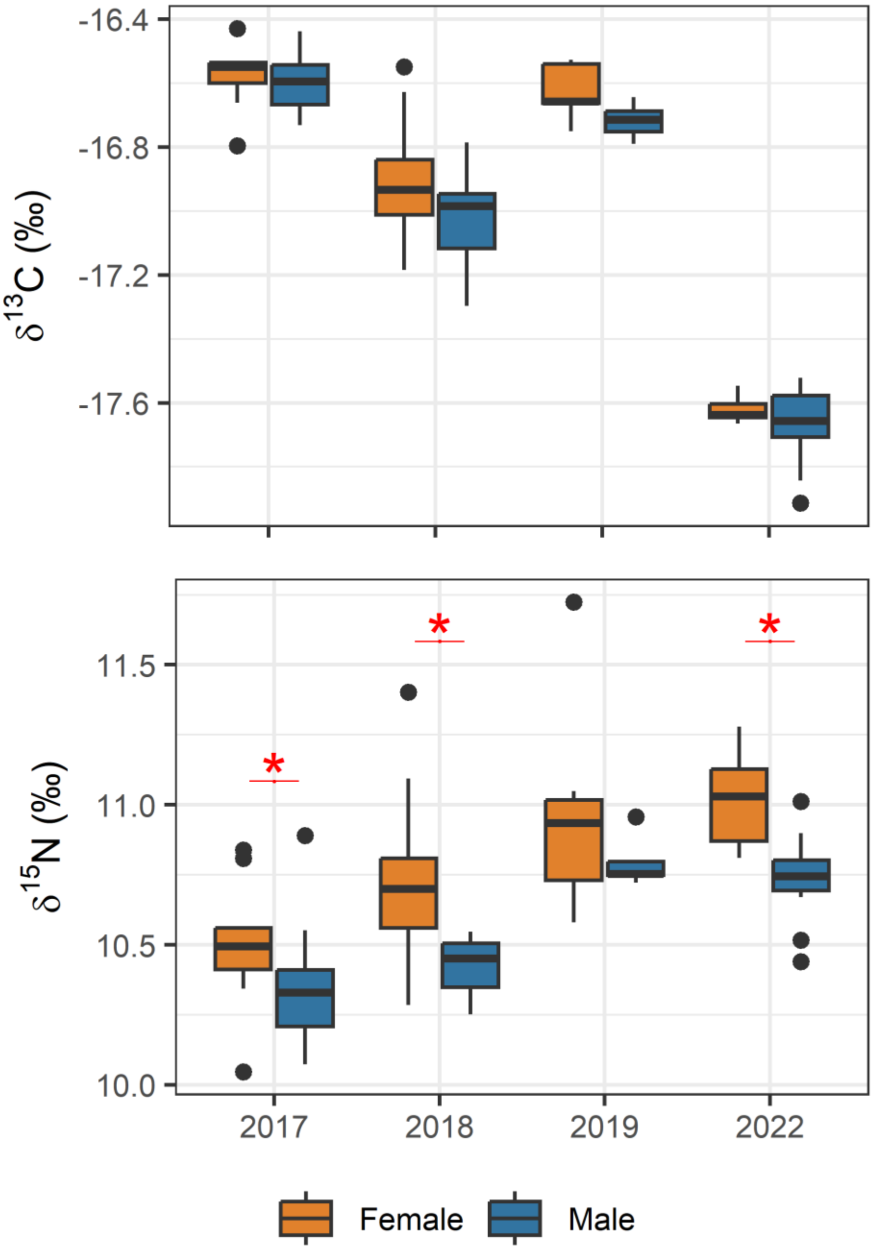

Fig. 2. Variations in $\delta^{13}C$ and $\delta^{15}N$ values in whole blood of males and females masked booby (*Sula dactylatra*) breeding in the Fernando de Noronha Archipelago, Brazil, from 2017 to 2022. *Significative differences between sexes

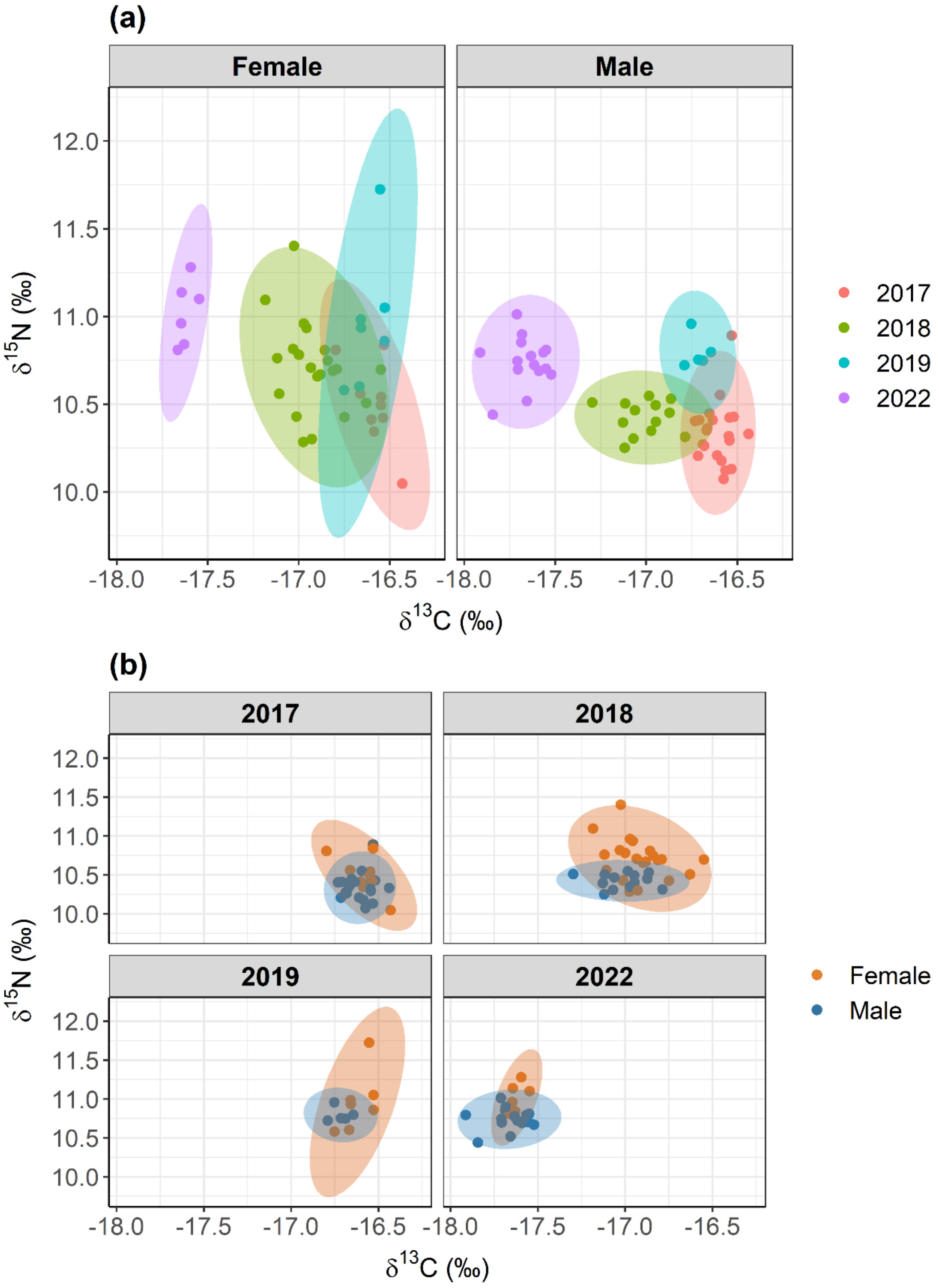

Fig. 3. (a) Bayesian ellipses of δ^{13}C and δ^{15}N values from whole blood samples of females and males of masked booby (*Sula dactylatra*) during breeding seasons in the Fernando de Noronha Archipelago; (b) Bayesian ellipses of δ^{13}C and δ^{15}N of males and females in each sampling year

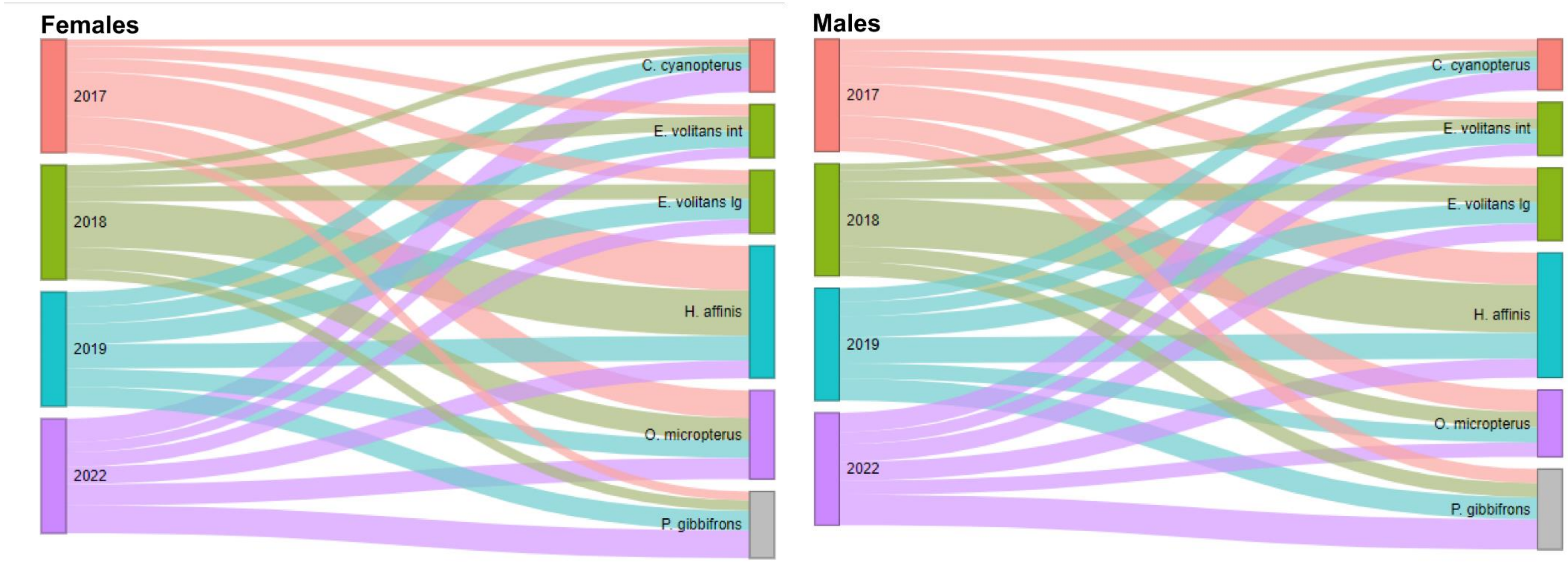

Fig. 4. Sankey diagram showing proportions of prey contribution estimated by stable isotopes mixing models (*Cheilopogon cyanopterus*, *Exocoetus volitans*, *Hirundichthys affinis*, *Oxyporhampus micropterus*, *Prognichthys gibbifrons*) for male and female of masked booby (*Sula dactylatra*) during breeding seasons (March–April) in the Fernando de Noronha Archipelago. int = intermediate size (100–150 mm); lg = large size (> 150 mm)

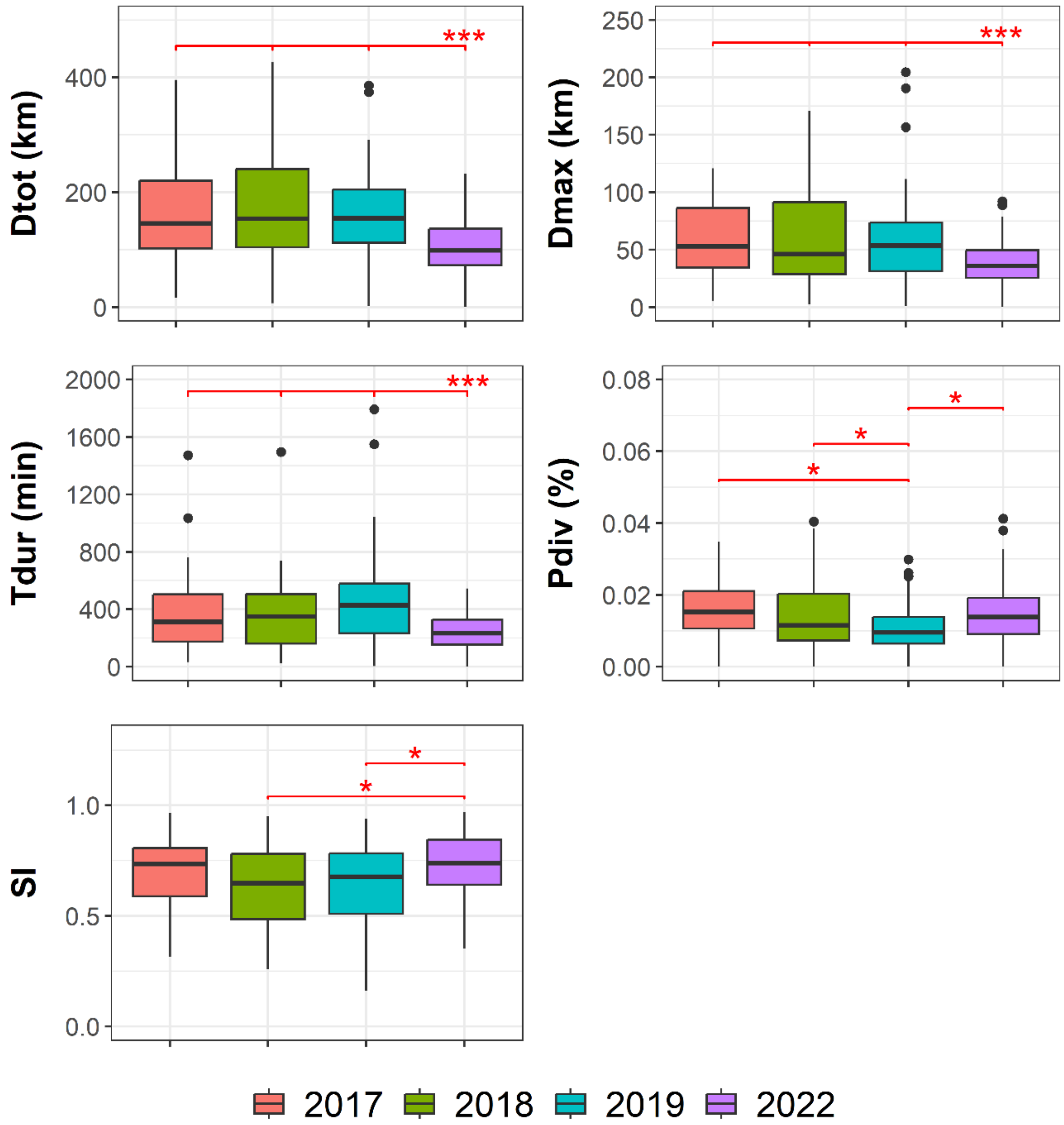

Fig. 5. Trip total distance traveled (D_{tot}, km), trip maximal distance from the colony (D_{max}, km), trip duration (T_{dur}, min), proportion of time diving (P_{div}, %) and straightness index (SI) of the foraging trips of masked boobies (*Sula dactylatra*) during the breeding seasons in the Fernando de Noronha Archipelago by year. *Significative differences between linked years; ***Significative differences between the year below and all the linked years

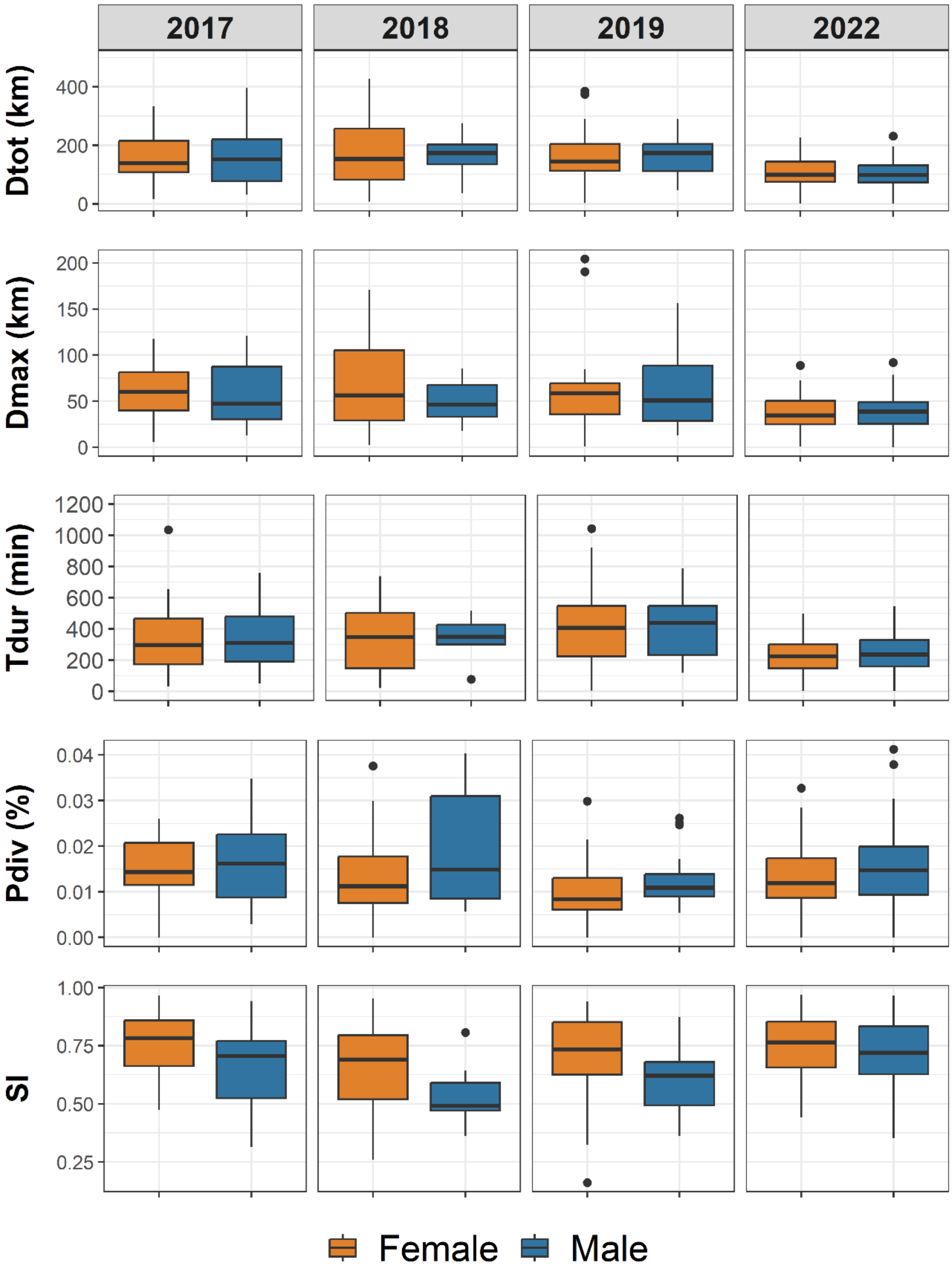

Fig. 6. Trip total distance traveled (D_{tot}, km), trip maximal distance from colony (D_{max}, km), trip duration (T_{dur}, min), proportion of time diving (P_{div}, %) and straightness index (SI) of the foraging trips of male and female masked boobies (*Sula dactylatra*) during breeding seasons in the Fernando de Noronha Archipelago in 2017, 2018, 2019 and 2022. No statistical difference was observed between the sexes for any metric in any year

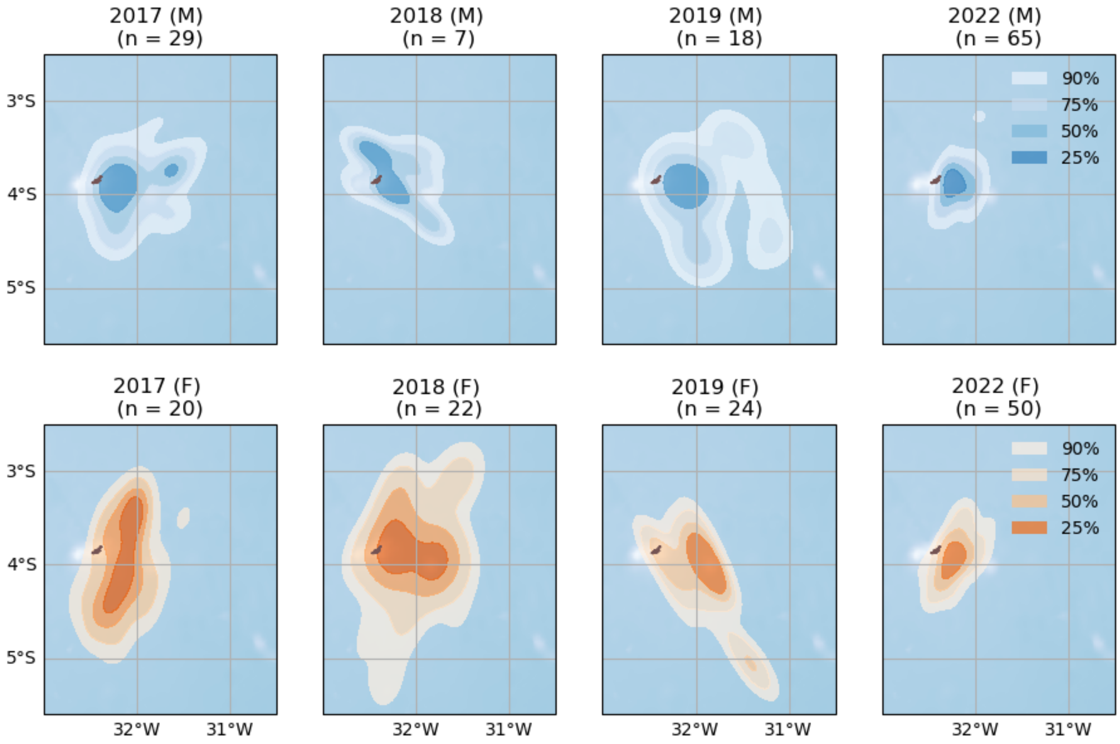

Fig. 7. Foraging distributions obtained by Kernel Density Estimation using 25%, 50%, 75%, and 90% contours of the kernel utilization distribution based on observed and predicted dives of males (M; blue) and females (F; orange) of masked booby (*Sula dactylatra*) during breeding seasons in the Fernando de Noronha Archipelago in 2017, 2018, 2019 and 2022. n = number of foraging trips

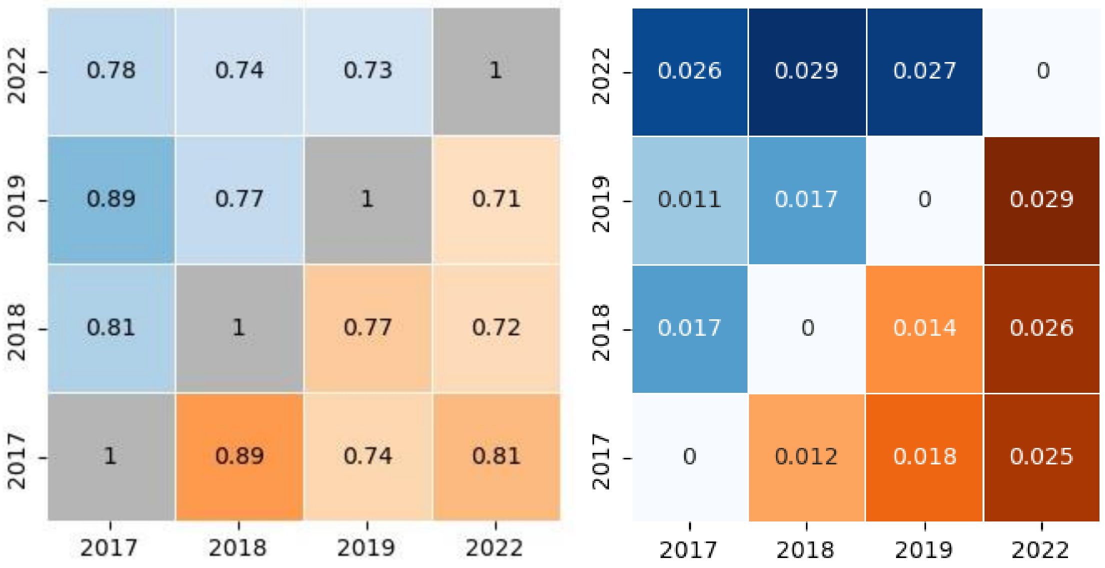

Fig. 8. Interannual pairwise overlaps in foraging areas of masked boobies (*Sula dactylatra*) around Fernando de Noronha Archipelago based on the Bhattacharyya coefficient (left) and the Root Mean Squared Error (right). Males are represented above the diagonal (bluish tones), while females are below the diagonal (orange tones)

SUPPLEMENTARY MATERIAL

Table S1. Standard area and overlap of Bayesian ellipses of δ^{13}C and δ^{15}N from whole blood samples of breeding masked booby *Sula dactylatra* in the Fernando de Noronha Archipelago by year. Ellipse areas represent 95% of the data.

Year	**Area**		**Overlap area**	**Overlap proportion (%)**
	Female	**Male**		
2017	0.41	0.27	0.21	30.88
2018	0.76	0.27	0.21	20.39
2019	0.59	0.13	0.12	16.67
2022	0.15	0.31	0.09	19.57

4. CAPÍTULO 2 - Breaking the bread on a tropical island: trophic niche partitioning of sympatric seabirds during breeding and non-breeding seasons

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Breaking the bread on a tropical island: trophic niche partitioning of sympatric seabirds during breeding and non-breeding seasons in western Atlantic Ocean

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ABSTRACT

The coexistence of seabirds with similar ecological requirements is challenging, especially during the breeding season when energy demands for chick rearing are high. In contrast, there are no nesting constrains during the non-breeding period, resulting in less intensive resource exploitation. Here, we aimed to test trophic niche differences between masked boobies (*Sula dactylatra*, MB) and red-footed boobies (*S. sula*, RFB) during their breeding and non-breeding seasons, which occur chronologically alternately in the Fernando de Noronha archipelago. We used stable isotope data of carbon (δ^{13}C) and nitrogen (δ^{15}N) from blood samples collected between 2015 and 2022. Most of δ^{13}C and δ^{15}N values were significantly lower for RFB than for MB, while MB exhibited larger isotopic niches throughout all sampled periods. In September, during MB non-breeding and RFB breeding season, the isotopic niche of both species was larger than in April, during the MB breeding and RFB non-breeding seasons. Additionally, the overlap between the two species remained low regardless of the period. The results reveal a marked niche partitioning between two sympatric seabird species in a tropical Atlantic colony, which may be influenced by the competitive advantages of MB, such as its larger body size and weight. Furthermore, RFB may adjusts not only its foraging strategies but also its breeding strategies based on the variation in the intensity of resource exploitation by MB during its annual reproductive cycle. Therefore, this study emphasizes that trophic niche partitioning plays an important role in enabling species coexistence and also may influence breeding phenology of seabirds.

KEY WORDS: breeding phenology, coexistence, ecological release, Sulidae, stable isotopes.

1. Introduction

The coexistence of species with similar ecological requirements represents a challenge to individual survival and population persistence, given the overlap in the use of limiting resources, leading to competition at intra- and interspecific levels (Gause 1932; Hardin 1960). Therefore, niche partitioning is an alternative strategy to dependence on similar resources, as it consists of adjusting one or more dimensions of the n-dimensional niche in order to avoid competition and allow coexistence (Hutchinson 1957; Schoener 1974). In this context, top predators such as seabirds are ideal models for niche partitioning studies, as they share similar life histories, breed in multispecies colonies, use available resources around the colony for their own feeding and offspring provisioning, and can occur in sympatry during both breeding and non-breeding periods (Petalas et al. 2024).

Breeding represents a stressful period, as the need to provide sustenance for both parents and the offspring requires high energy expenditure and consequently, intense exploitation of resources (Barger et al. 2016; Fromant et al. 2022). Overall, seabirds are central-place foragers during the breeding period, which means that they return to the nest periodically between foraging trips (Schreiber and Burger 2001). This implies an exploitation of the resources available around the colony by one or more species, especially during chick-rearing, so that the offspring are constantly fed with lower energy costs for the parents (Jessopp et al. 2020). Additionally, birds may also be more selective regarding the types of prey, directing efforts toward capturing resources that best fit chick requirements (González-Medina et al. 2017; Piña-Ortiz et al. 2024). On the other hand, birds may explore resources in broader areas and/or a greater prey diversity during the non-breeding period, as they do not have the commitment of caring for the chick (Lisnizer and Yorio 2019; Mills et al. 2021; Roy et al. 2021), which may be crucial for developing adequate body conditions for the next breeding season (Desprez et al. 2018; Hovinen et al. 2019). Thus, the breeding and non-breeding periods are stages of the avian life cycle that require distinct strategies and promote different patterns of behavior. However, the presence of a competing species, whether permanent or temporary in both periods, increases competitive pressures and requires adjustments of foraging strategies to enable niche partitioning (Young et al. 2010a; Almeida et al. 2021).

Niche partitioning is an essential process to reduce competition and allow for the coexistence of seabirds (Ashmole and Ashmole 1967; Jessopp et al. 2020). The different strategies developed to avoid competition may be related to foraging behavior, through which species can explore distinct areas at different distances from the colony, which may also result in the consumption of different prey (Barger et al. 2016; Fromant et al. 2022; Fayet et al. 2023). Additionally, foraging or diving at different depths in the water column can also contribute to the variation in captured prey (Kappes et al. 2011; Petalas et al. 2021). In these cases, morphological factors such as body size and mass may play an important role, as they influence flight capability, prey capture strategy, diving depth, and sizes of consumed prey (Lewis et al. 2005; Catry et al. 2009; Mancini and Bugoni 2014). Finally, interspecific variations in breeding phenology may be alternatives to allow coexistence, so that each species goes through the breeding stress at different times.

Temporal variations in resource use can also contribute to niche partitioning, especially in non-migratory species. The more intensive use of resources by one species during the breeding period may contribute to increased competition with other resident species (Young et al. 2010a; Mancini et al. 2014) or seasonal species in the colonies (Almeida et al. 2021; Carreiro et al. 2022). In this context, year-round coexistence may contribute to the development of different foraging and breeding strategies, allowing species to exploit resources simultaneously (Soanes et al. 2021; Lerma et al. 2024). This balance between more and less intense exploitation during breeding and non-breeding periods can illustrate the concept of ecological release, which involves altering the ecological niche according to more or less intense interspecific interactions (Herrmann et al. 2021). This concept could be illustrated through inverse periods of reproduction, where the species in breeding activity may exhibit a narrower niche, associated with the exploitation of resources near the colony and more energetically demanding. Simultaneously, the species in the non-breeding period may present broader niches, as they can exploit resources more widely and diversely. Such strategies can be crucial for promoting and maintaining local biodiversity, especially in environments of low food resource availability.

Competition for resources and niche partitioning can be intensified in locations with scarce resources, such as tropical oceans. In these regions, resource availability is ephemeral and patchily distributed (Longhurst and Pauly 1987), making foraging sites for seabirds less predictable (Weimerskirch et al. 2006). Boobies (Aves: Suliformes: Sulidae: *Sula* spp.) are seabirds that occur in tropical and subtropical environments and commonly form multispecies colonies (Nelson 1978). For example, masked boobies (*Sula dactylatra*, hereafter MB) have larger body size and mass than red-footed boobies *(S. sula*, hereafter RFB) (Nelson 1978; Young et al. 2010b), and both species exhibit reverse sexual dimorphism, i.e., females larger and heavier than males (Nelson 1978; Lewis et al. 2005). Previous studies in the Pacific and Indian Oceans comprising both species demonstrated differences in foraging strategies: MB usually forage closer to the colony and their diet mainly consists of flying fish, while RFB tends to forage in more oceanic environments and feed on a higher proportion of squid (Young et al. 2010b; Kappes et al. 2011; Almeida et al. 2021). In the Fernando de Noronha archipelago, located in the tropical Atlantic Ocean, both species occur in sympatry along with nine other breeding seabird species (Mancini et al. 2016), remaining in the archipelago year-round and using the colonies as roosting sites during non-breeding periods. MB has peaks in nesting activity between February and May, while RFB breeds mainly from July to October (Serafini et al. 2024), and thus such variations in breeding peaks suggest the need to develop local adaptation strategies to partition resources and allow the coexistence of both species.

Stable isotope analysis (SIA) is a widely used technique for studying seabird trophic ecology as it allows the investigation of potential differences in foraging strategies between species and between periods of the annual life cycle (Petalas et al. 2024). For example, carbon isotopic ratios (δ^{13}C) inform spatial aspects of the diet, such as the relationship between the use of inshore or offshore areas (Hobson et al. 1994; Cherel and Hobson 2007). Additionally, nitrogen isotopic ratios (δ^{15}N) are markers of trophic position, shedding light on prey-predator relationships (Hobson et al. 1994; Fry 2006). Thus, by using isotopic values as two-dimensional coordinates, the δ-space represents the isotopic niche, which is considered a proxy for trophic niche (Newsome et al. 2007; Jackson et al. 2011). Isotopic measurements can be obtained from different tissues, which have different turnover rates (Vander Zanden et al. 2015). In the case of seabirds, blood represents a turnover of 12-15 days (Hobson and Clark 1993), providing a suitable temporal window for inter-seasonal studies (Dalerum and Angerbjörn 2005). Therefore, SIA is a tool that allows testing intra- and interspecific niche partitioning in the use of food resources in space and time (Cherel et al. 2008; Young et al. 2010a; Almeida et al. 2021).

In this context, we aimed to test differences in the trophic niche of two sympatric booby species in the Fernando de Noronha archipelago between the breeding and non-breeding periods of both species using an isotopic dataset systematically obtained from 2015 to 2022 for approximately 210 individuals. Given the coexistence of the two species in the archipelago and prior knowledge of morphological and behavioral characteristics of each species, we expected to (i) observe higher δ^{15}N in MB than RFB and (ii) identify niche segregation between the two species during all sampled periods. However, during the breeding period of each species, (iii) we expect the niches to be narrower compared to the non-breeding period, representing differences in the set of prey exploited in each period and illustrating the concept of ecological release.

2. Materials and methods

2.1 Study area

The birds were sampled on Ilha do Meio (3°49'11.6" S; 32°23'35.362" W), one of the 21 islets that comprise the Fernando de Noronha archipelago, located in the Western Atlantic Ocean, 360 km off the coast of Brazil (Fig. 1). The archipelago has a tropical climate, with an average temperature of 25°C and interannual variation in rainfall, with the rainy season from March to July and the dry season from August to January (Castro 2009). Despite this, the seasonal variation in sea surface temperature (SST) is small, with higher values from March to May (28°C) and lower values from August to November (~26.5°C) (Tchamabi et al. 2017). Fernando de Noronha is influenced by the central branch of the South Equatorial Current (cSEC) in the surface layer, and the South Equatorial Undercurrent (SEUC) in the lower layer (Costa da Silva et al. 2021) so that the waters surrounding the archipelago are considered oligotrophic (Farias et al. 2022). Meio Island covers around 160.000 m², most of which is covered in herbaceous vegetation and exposed soil, where colonies of masked and brown boobies occur. In addition, the northwest of the island has tree and shrub vegetation, where the red-footed booby colony is located (Gaiotto et al. 2022). Ilha do Meio has undergone a process of rat control between 2017 and 2018, as it had a high density of rats (*Rattus rattus*), which preyed on eggs and chicks, damaging reproduction.

2.2 Sampling methods

Sampling was carried out in April and September from 2015 to 2022, during the chick-rearing periods of the MB and RFB, respectively (Serafini et al. 2024). Blood samples from both species were collected during the fieldwork expeditions. For MB, samples during its breeding peak were collected in April 2017, 2018, 2019, and 2022, and non-breeding samples in September 2015, 2016, and 2018. For RFB, samples during its breeding peak were collected in September 2015, 2016, and 2018, and non-breeding samples in April 2019 and 2022. For this, individuals were captured manually or with a fishing pole, and 0.3ml of blood was collected from the metatarsal vein using sterile syringes/needles, which were then stored in microtubes. Individuals were banded or marked with crayons before being released to prevent resampling. Field procedures were authorized by SISBIO 64234 and approved by the Ethics Committee of Federal University of Rio Grande do Sul under number 37905.

2.3 Stable isotope analysis

In the laboratory, blood samples were lyophilized, ground, and homogenized, and subsamples of ~0.7 mg were placed in tin capsules for stable isotope analysis (SIA) of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) using an isotope ratio mass spectrometer at the *Pôle Spectrométrie Océan* of the *Institut Universitaire Européen de la Mer* (PSO-IUEM, France), and the *Centro Integrado de Análises* of the *Universidade Federal do Rio Grande* (CIA-FURG, Brazil). Procedures to remove lipids from the samples were not carried out due to their expected low concentration in the seabird blood (Bearhop et al. 2002). Differences between sample and standard ratios (Vienna Pee Dee Belemnite for $\delta^{13}C$; atmospheric air for $\delta^{15}N$) are expressed in δ notation in parts per thousand (‰). The accuracy of the measurements was checked by repeated analyses of internal samples of acetanilide at the PSO-IUEM, and glutamic acid and caffeine at the CIA-FURG.

2.4 Data analysis

To assess interspecific variations between MB and RFB, metrics of δ^{13}C and δ^{15}N (mean, standard deviation, minimum, maximum) were calculated for each expedition (month/year), considering only those when data from both species were collected. Thus, data from MB expeditions in April 2017 and 2018, when RFB were not sampled, were excluded from interspecific analysis. Additionally, univariate differences between the isotopic values of the two species in each expedition were tested using the Kruskal-Wallis test and the Mann-Whitney U test as a post-hoc using the False Discovery Rate for *P*-value adjustment (Benjamini and Hochberg 1995). Subsequently, the isotopic niches in each expedition were estimated in the R environment through a Bayesian approach implemented in the SIBER package (Jackson et al. 2011), considering 95% of the data. The same metrics and tests were applied to assess differences in isotopic values between breeding and non-breeding periods of MB, considering potential sex differences as well. Hence, seven samples with unidentified sexes were removed from the analysis. Additionally, isotopic niche from Bayesian ellipses was also estimated for each sampling event considering both periods.

3. Results

3.1 Interspecific comparisons of trophic niche

A total of 148 samples were obtained, with 80 from MB (33 from the breeding period and 47 from the non-breeding period) and 68 from RFB (58 from the breeding period and ten from the non-breeding period) (Table 1). For δ^{13}C, the means ranged from -18.28 ± 0.47‰ for RFB in September 2015 to -16.66 ± 0.09‰ for MB in April 2019. Additionally, for δ^{15}N, the means ranged from 10.28 ± 0.19‰ for RFB in April 2022 to 11.51 ± 0.21‰ for MB in September 2015 (Table 1). The δ^{13}C and δ^{15}N values of RFB were significantly lower than those of MB in all expeditions ($P<0.01$), except for September 2015 ($P=0.03$)

(Fig. 2, Table S1). Additionally, MB exhibited larger isotopic niches than RFB in all sampling events, except for September 2016 (Table 2). Finally, overlap between the two species was less than 13% in all expeditions, with the highest overlaps observed in September (9.13 to 12.78%) and the lowest in April (1.89 to 3.02%) (Table 2).

3.2 Intraspecific variations in masked boobies

A total of 137 blood samples from MB were analyzed, with 97 during the breeding period (43 females and 54 males) and 40 during the non-breeding period (19 females and 21 males) (Table 3). During the breeding period, the δ^{13}C means ranged from -17.66 ± 0.11‰ in April 2022 (males) to -16.58 ± 0.1‰ in April 2017 (females), and for δ^{15}N, it ranged from 10.34 ± 0.18‰ in April 2017 (males) to 11.56 ± 0.33‰ (females) in September 2015 (Table 3). In general, δ^{13}C values were significantly higher in breeding periods compared to non-breeding periods ($P<0.01$), and the opposite was observed for δ^{15}N values, which were significantly higher in the non-breeding period compared to the breeding period ($P<0.01$). Significant differences in δ^{13}C were found between most periods ($P<0.01$), except between September 2015 and April 2022, between September 2016 and April and September 2018, between April 2017 and 2019, and between April and September 2018 (Fig. 4). For δ^{15}N, the differences were significant between all expeditions, except between September 2015 and 2016 and between April 2019 and 2022 ($P>0.01$) (Fig. 4). Between sexes, the differences were significant only in September 2016 for δ^{13}C, and in April 2017, 2018, 2022, and September 2018 for δ^{15}N (Fig. 4). The isotopic niches in the non-breeding period are located above the niches of the breeding period in δ-space, indicating higher δ^{15}N values. Furthermore, there is a partial overlap of isotopic niche between the periods, especially between September 2015 and the other non-breeding periods and breeding periods of 2018, 2019, and 2020. The non-breeding periods of 2016 and 2018 partially overlap only with the breeding periods of 2018 and 2019 (Fig. 5).

4. Discussion

In this study, we demonstrated niche partitioning strategies between two sympatric seabird species coexisting in a colony in the tropical Atlantic Ocean, as well as evidenced seasonal variations in foraging strategies between breeding and non-breeding periods. MB had higher δ^{15}N values than RFB and higher δ^{13}C values as expected given differences in body size and mass. Both species showed low niche overlap regardless of the sampling event, indicating that trophic niche partitioning plays an important role in enabling species coexistence throughout the year. This may result from distinct foraging strategies, including spatial distribution and diet. However, this partitioning may also be influenced by the competitive advantages of MB, due to its body and population size in Fernando de Noronha. In this sense, it is possible that MB varies the intensity of resource exploitation according to its breeding cycle and that RFB adapts its foraging and breeding strategies based on MB. Additionally, MB shows marked variation between breeding and non-breeding periods, with few subtle intersexual differences. Thus, this study highlighted a strong niche partitioning between sympatric species in a tropical environment and how interspecific interactions may influence changes in ecological niche and breeding behavior, illustrating the concept of ecological release.

The isotopic niches of RFB and MB showed low overlap across all compared periods, which can be potentially associated with morphological characteristics and colony size, which affect physiological differences and may also confer advantages in resource competition. MB, which are larger and can be up to twice as heavy as RFB, presented higher δ^{15}N values than RFB, which is the smallest species in the *Sula* genus (Nelson 1978; Young et al. 2010b). This characteristic results not only in higher energy requirements for MB but also in advantages in acquiring higher range of prey species and sizes in greater depths, and therefore, contribute to it higher δ^{15}N values (Kappes et al. 2011; Mancini et al. 2014, Lerma et al. 2024). In this sense, the morphological advantages of MB may contribute to restricting the prey consumed by RFB through intensive resource exploitation, especially during breeding periods. Additionally, colony size may also influence diet. In Palmyra Atoll, where the RFB colony is significantly larger than that of MB (1000-2500 breeding pairs and 10-50 pairs, respectively), RFB predominantly feed on flying fish, and no significant differences in nitrogen were observed between the species (Young et al. 2010b). However, the opposite scenario occurs on Tromelin Island and Clarion Island, where MB population is smaller than RFB and squid represents more than half of the biomass consumed by RFB (Kappes et al. 2011) or are more present in RFB diet than in MB (Lerma et al. 2024). In Fernando de Noronha, the populations of the two species are relatively similar in size, with MB having 400 individuals and RFB having 730 individuals (Mancini et al. 2016). Therefore, it is possible that the population size of MB may contribute to intensifying its competitive advantages over smaller species, such as RFB (Mendez et al. 2017).

The low isotopic niche overlap between species can also be associated with different strategies in the use of space. Carbon values for RFB were significantly lower than those for MB in all periods, suggesting a more oceanic distribution for RFB in Fernando de Noronha, as regions farther from the archipelago tend to have more depleted carbon values (Cherel and Hobson 2007; Mancini and Bugoni 2014). The use of distant areas from the colony for foraging in RFB, compared to other Sulidae, was also observed in other colonies during both breeding and non-breeding periods, such as in Palmyra Atoll (Young et al. 2010b), Cayman Islands (Austin et al. 2021), and Raso Islet (Almeida et al. 2021). Additionally, the significantly higher nitrogen values for MB may be associated with differences in diet or trophic levels of consumed prey (Cherel and Hobson 2007). In some colonies, RFB are associated with a higher consumption of squid, a less energetic than fish (Clarke and Prince 1980), compared to the diet of other species of boobies, which mainly feed on flying fish (Kappes et al. 2011; Austin et al. 2021; Lerma et al. 2024), although this is not a consistent pattern (Harrison et al. 1983; Weimerskirch et al. 2006). However, with the methodology applied in this study, it is not possible to assert that RFB feeds more on flying fish or squid in Fernando de Noronha, although the significantly lower nitrogen values compared to MB may suggest a diet consisting of smaller prey or lower trophic levels in RFB (Romanuk et al. 2011).

The potential competitive advantages of MB over RFB can also be perceived by observing the variation in the width of their isotopic niches in each period of their annual cycles. For resident species and central-place foragers, it is expected that there will be greater restrictions on prey diversity and size, as well as a reduction in foraging areas, during the chick-rearing period, resulting in narrower niches (Cherel et al. 2007; 2008). The opposite pattern is expected during the non-breeding period when parental restrictions are relieved, and birds can diversify their diet and forage in areas farther from the colony (Lisnizer and Yorio 2019; Roy et al. 2021). Indeed, this can be subtly observed for MB, considering the larger isotopic niche area observed in September compared to April, corroborating a previous study indicating a more oceanic behavior of MB during the non-breeding period in Fernando de Noronha (Roy et al. 2021). However, RFB deviates from the expected pattern, as its niche area is larger during its breeding period in September than during the non-breeding period in April. This pattern of RFB may be related to the concept of ecological release (Herrmann et al. 2021) since RFB's niche would be altered according to the greater and lesser intensity of resource exploitation by MB in its breeding and non-breeding periods, respectively. These findings suggest that in September, RFB could exploit optimal resources because MB is in the non-breeding period, and so RFB would adjust its breeding activity to this period. A similar situation occurs in Cabo Verde, where the seasonal presence of RFB in brown booby (*S. leucogaster*) colonies, which breeds year-round, potentially contributes to increased sexual segregation, reducing foraging areas (Almeida et al. 2021), as well as variations in the diet of brown boobies (Carreiro et al. 2022). In addition, the brown boobies that breed on Ilha do Meio have their reproductive period between November and January, and their reproductive period does not coincide with MB and RFB (authors' pers. obs.). Thus, competitive advantages of MB associated with periods of greater or lesser intensity of resource use would potentially influence the niche width of RFB, and the opposite is not observed, reinforcing a dominant position of MB in resource use in the archipelago (Kappes et al. 2011).

The stable isotope analysis provides important insights into niche partitioning among species as well as seasonal variations in spatial and dietary levels. However, its interpretations are limited and dependent on multiple factors, such as variations in baselines over time and space that influence isotopic values in marine environments (Mancini and Bugoni 2014; Magozzi et al. 2017). Specifically, Fernando de Noronha is directly influenced by the central arm of the South Equatorial Current (cSEC), which can show seasonal variations in intensity (Costa da Silva et al. 2021), and consequently may influence the spatial distribution of nutrients, productivity, and biomass in its surroundings, which influence the trophic web at different levels (Salvetat et al. 2022; Eduardo et al. 2023). Thus, such dynamics could indeed influence isotopic baselines inter- and intra-annually, potentially contributing to increased significant differences between isotopic values seasonally (Eduardo et al. 2023). However, considering other studies that used SIA in the archipelago, no isotopic variations were observed between seasons in the same year for MB (Mancini et al. 2014), as observed in this study in 2018, nor between seasons and years in subsurface predators (Martins et al. 2021). This suggests that isotopic differences between breeding periods may be more associated with temporal variations in food availability around Fernando de Noronha than baseline fluctuations. Another potential factor that may influence the interpretations of isotopic niches is the low sample size, especially for RFB during the non-breeding period, which may statistically influence the results, leading to narrower isotopic niches. However, even with a low sample size, it was possible to identify a similar pattern of low overlap between species niches between non-consecutive years (2019 and 2022), which contributes to the reliability of the results obtained. Additionally, the use of blood samples during the non-breeding period provides greater reliability of isotopic values than feathers, previously used in studies with boobies (Young et al. 2010a; 2010b; Pontón-Cevallos et al. 2017), since these species may not exhibit a marked molting pattern (Nelson 1978).

The present study demonstrates the outcome of a local adaptation process to allow the coexistence of two species with similar ecological requirements. The intense pressures potentially exerted by MB during its breeding period may have contributed to other species, such as RFB, adapting to adjust the timing of their breeding activity to periods with lower competitive pressures, illustrating the concept of ecological release. Thus, this represents a potential plasticity not only of foraging but also of breeding strategies (e.g. breeding phenology) in response to competition for resources, suggesting a connection between them (Soanes et al. 2021). However, MB and RFB are just two of the 11 species that breed in the archipelago (Mancini et al. 2016), and thus, it would be interesting to explore resource partitioning at an assembly level of seabirds in order to understand how these species interact in space and time, shedding light on processes promoting and maintaining biodiversity in oligotrophic regions.

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Data/code availability: Data and code are available on our GitHub page https://github.com/SeabirdEcologyUFRGS/SIA_FdN .

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TABLES

Table 1. Mean ± standard deviation (SD) of carbon (δ^{13}C) and nitrogen (δ^{15}N) isotopic ratios from blood samples of masked booby *Sula dactylatra* and red-footed booby *S. sula* from Fernando de Noronha archipelago separated by sampling event (month/year). Se= season, Br = breeding, Nbr = non-breeding.

Month /year	**masked booby**						**red-footed booby**					
			δ^{13}C		**δ^{15}N**				**δ^{13}C**		**δ^{15}N**	
	Se	**n**	**Mean ± SD**	**Min | Max**	**Mean ± SD**	**Min | Max**	**Se**	**n**	**Mean ± SD**	**Min | Max**	**Mean ± SD**	**Min | Max**
Set/2015	NBr	10	-17.72±0.75	-19.14 | -16.72	11.51±0.21	11.16 | 11.90	Br	12	-18.28±0.47	-19.43 | -17.81	10.95±0.18	10.64 | 11.26
Set/2016	NBr	22	-17.03±0.13	-17.31 | -16.78	11.44±0.2	11.09 | 11.77	Br	29	-17.39±0.18	-18.11 | -17.10	10.97±0.2	10.57 | 11.37
Set/2018	NBr	15	-17.0±0.15	-17.29 | -16.74	11.24±0.21	10.75 | 11.48	Br	17	-17.45±0.16	-17.74 | -17.12	10.56±0.19	10.3 | 10.96
Apr/2019	Br	12	-16.66±0.09	-16.79 | -16.53	10.89±0.3	10.58 | 11.72	NBr	4	-16.98±0.06	-17.01 | -16.89	10.37±0.07	10.29 | 10.46
Apr/2022	Br	21	-17.65±0.10	-17.91 | 17.52	10.82±0.2	10.44 | 11.28	NBr	6	-17.92±0.03	-17.96 | -17.89	10.28±0.19	10.05 | 10.60

Table 2. Standard area and overlap of Bayesian ellipses of δ^{13}C and δ^{15}N from whole blood samples of masked booby *Sula dactylatra* and red-footed booby *S. sula* during sampling events (month/year) in the Fernando de Noronha archipelago. Ellipse areas represent 95% of the data.

Month/Year	**Area**		**Overlap area**	**Overlap proportion (%)**
	masked	**red-footed**		
Sep/2015	3.13	1.74	0.58	11.99
Sep/2016	0.48	0.53	0.13	12.78
Sep/2018	0.52	0.46	0.09	9.13
Apr/2019	0.44	0.11	0.02	3.02
Apr/2022	0.36	0.12	0.01	1.89

Table 3. Mean ± standard deviation (SD) of isotopic ratios of carbon (δ^{13}C) and nitrogen (δ^{15}N) from blood samples of females and males of masked booby *Sula dactylatra* from Fernando de Noronha archipelago separated by sampling event (month/year). Br = breeding, Nbr = non-breeding.

Sampling event/ Season		**female**							**male**						
			δ^{13}C (‰)			**δ^{15}N (‰)**				**δ^{13}C (‰)**			**δ^{15}N (‰)**		
		n	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**n**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**
Set/2015	Nbr	4	-17.34±0.44	-17.69	-16.72	11.56±0.33	11.16	11.9	3	-17.53±0.51	-18.12	-17.19	11.44±0.03	11.41	11.46
Set/2016	Nbr	11	-16.96±0.1	-17.09	-16.78	11.4±0.21	11.09	11.72	10	-17.10±0.11	-17.31	-16.98	11.49±0.19	11.24	11.77
Apr/2017	Br	9	-16.58±0.1	-16.80	-16.43	10.50±0.24	10.05	10.84	21	-16.61±0.08	-16.73	-16.44	10.34±0.18	10.07	10.89
Apr/2018	Br	21	-16.92± 0.16	-17.18	-16.55	10.71±0.26	10.28	11.40	13	-17.01±0.14	-17.30	-16.79	10.42±0.10	10.25	10.55
Set/2018	NBr	4	-16.93±0.16	-17.13	-16.44	11.43±0.04	11.36	11.48	8	-17.07±0.14	-17.29	-16.86	11.14±0.2	10.75	11.40
Apr/2019	Br	7	-16.62±0.09	-16.75	-16.53	10.96±0.38	10.58	11.72	5	-16.72±0.06	-16.79	-16.64	10.80±0.10	10.72	10.96
Apr/2022	Br	6	-17.62±0.04	-17.67	-17.55	11.02±0.18	10.81	11.28	15	-17.66±0.11	-17.91	-17.52	10.74±0.14	10.44	11.01

FIGURES

Fig. 1. Ilha do Meio, at the Fernando de Noronha archipelago, where is located the colonies of masked booby *Sula dactylatra* and red-footed booby *S. sula*.

Fig. 2. Variations in δ^{13}C and δ^{15}N values of masked booby *Sula dactylatra* and red-footed booby *S. sula* during sampling events (month/year) in the Fernando de Noronha archipelago. April (Apr) is the breeding season for the masked booby and non-breeding season of red-footed booby, and the opposite occurs in September (Sep).

Fig. 3. Bayesian ellipses of δ^{13}C and δ^{15}N from whole blood samples of masked booby *Sula dactylatra* and red-footed booby *S. sula* during sampling events (month/year) in the Fernando de Noronha archipelago. April is breeding season for the masked booby and non-breeding season of red-footed booby, and the reverse pattern occurs in September. The ellipses represent 95% of the data.

Fig. 4. Variations in δ^{13}C and δ^{15}N values for males and females of masked booby *Sula dactylatra* breeding in the Fernando de Noronha archipelago in each expedition. Sep = September, non-breeding season; Apr = April, breeding season.

Fig. 5. Bayesian ellipses of δ^{13}C and δ^{15}N from whole blood samples of masked booby *Sula dactylatra* during breeding and non-breeding seasons in the Fernando de Noronha archipelago in each sampling years.

Fig. 1

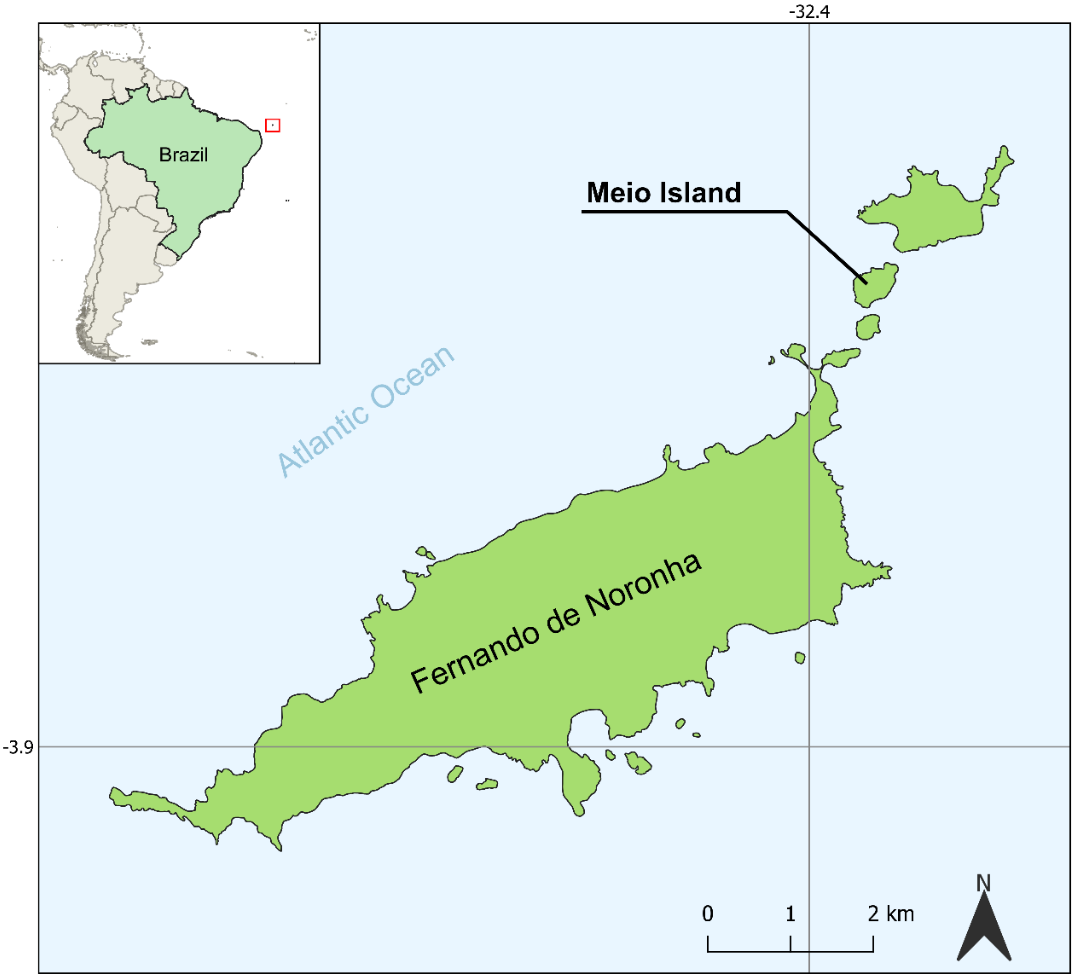

-32.4
-3.9
Brazil
Meio Island
Atlantic Ocean
Fernando de Noronha
0
1
2 km
N

Fig. 2

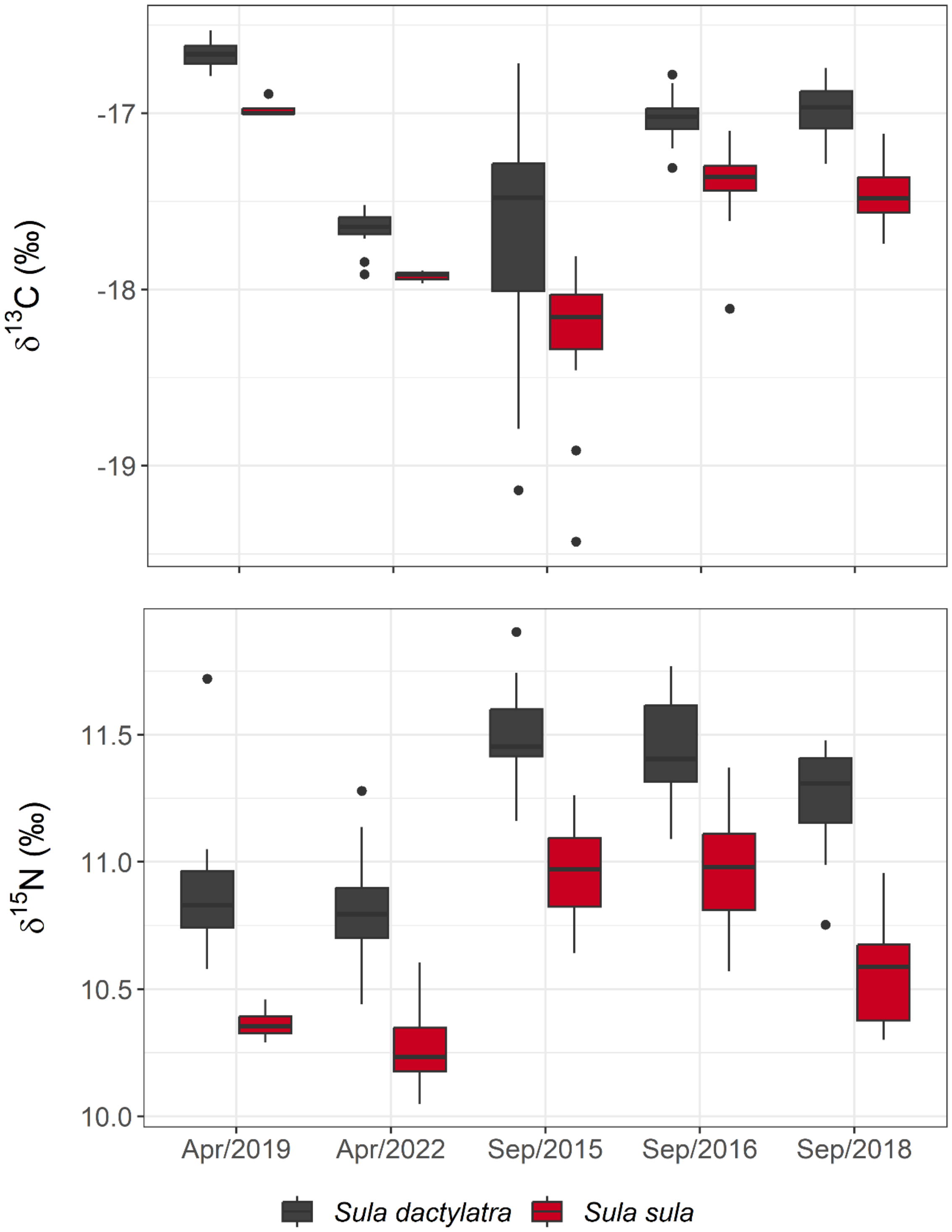

δ13C (‰)
-17
-18
-19
δ15N (‰)
11.5
11.0
10.5
10.0
Apr/2019
Apr/2022
Sep/2015
Sep/2016
Sep/2018
Sula dactylatra
Sula sula

Fig. 3

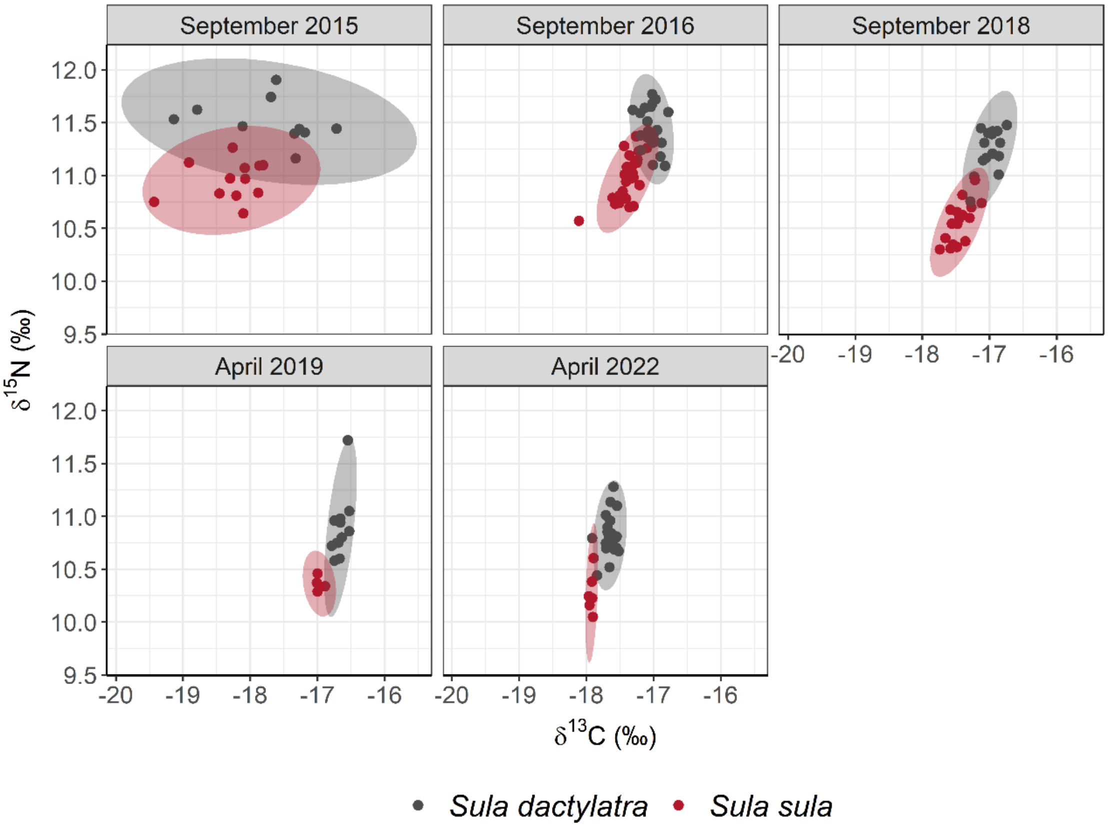

September 2015
September 2016
September 2018
April 2019
April 2022
12.0
11.5
11.0
10.5
10.0
9.5
-20
-19
-18
-17
-16
$\delta^{15}N$ (‰)
$\delta^{13}C$ (‰)
● *Sula dactylatra* ● *Sula sula*

Fig. 4

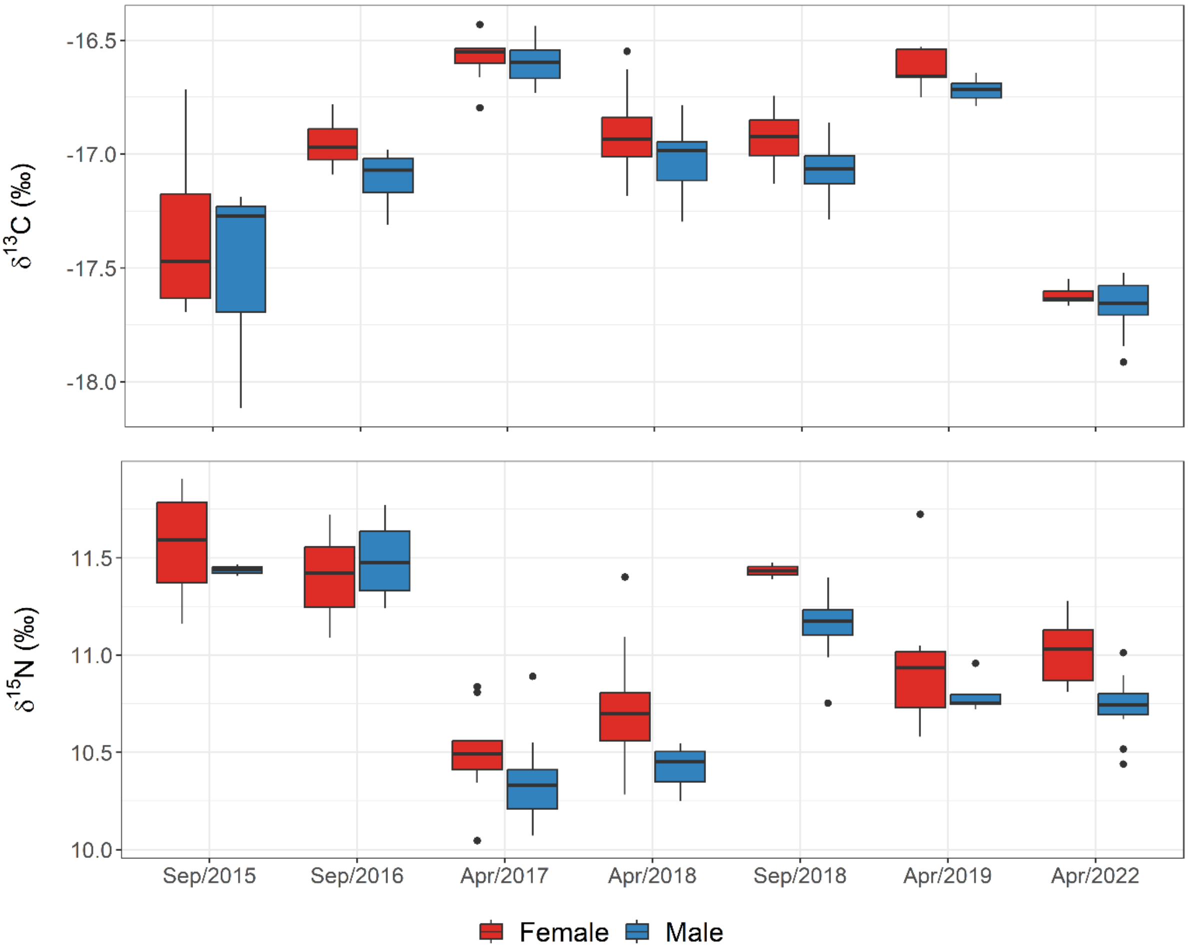
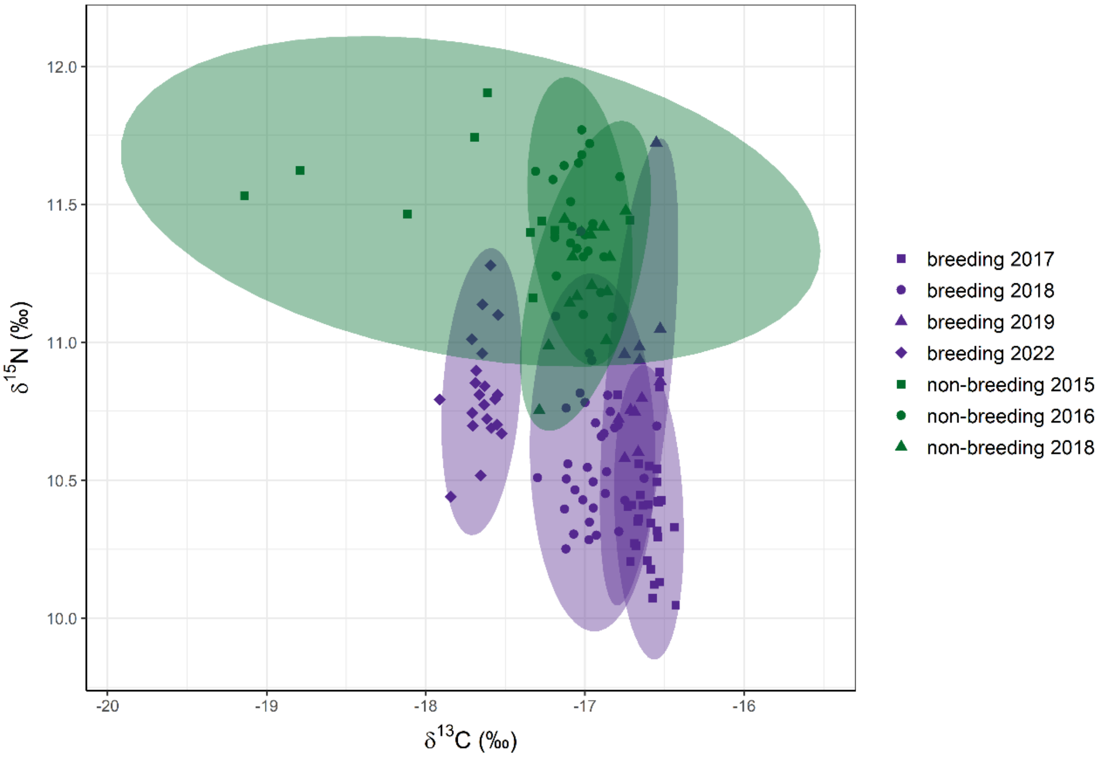

-16.5
-17.0
-17.5
-18.0
$\delta^{13}C$ (‰)
11.5
11.0
10.5
10.0
$\delta^{15}N$ (‰)
Sep/2015
Sep/2016
Apr/2017
Apr/2018
Sep/2018
Apr/2019
Apr/2022
Female
Male

Fig. 5


12.0
11.5
11.0
10.5
10.0
$\delta^{15}N$ (‰)
-20
-19
-18
-17
-16
$\delta^{13}C$ (‰)
breeding 2017
breeding 2018
breeding 2019
breeding 2022
non-breeding 2015
non-breeding 2016
non-breeding 2018

Supplementary Material

Table S1. Results from Kruskal-Wallis test (X^2) and post-hoc Mann-Whitney U test (*P*) of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic ratios from blood samples between masked *Sula dactylatra* and red-footed boobies *S. sula* from Fernando de Noronha archipelago in each sampling event (month/year).

Month/year	**$\delta^{13}C$**		**$\delta^{15}N$**	
	X^2	*P*	X^2	*P*
Sep/2015	4.73	0.02	15.14	<0.01
Sep/2016	33.78	<0.01	30.41	<0.01
Sep/2018	21.10	<0.01	22.46	<0.01
Apr/2019	8.52	<0.01	8.48	<0.01
Apr/2022	12.25	<0.01	12.66	<0.01

5. CONSIDERAÇÕES FINAIS

No presente estudo, foram caracterizadas as estratégias de forrageio do atobá-mascarado (*S. dactylatra*) e do atobá-de-pé-vermelho (*S. sula*) no arquipélago de Fernando de Noronha através de dados de rastreamento remoto e isótopos estáveis. O conjunto de dados utilizou informações de cerca de 210 indivíduos amostrados durante sete expedições realizadas entre 2015 e 2022, englobando períodos reprodutivos e não-reprodutivos das espécies. A partir dos resultados obtidos, foi possível observar padrões nas áreas de forrageio exploradas e variações interanuais, além de investigar a partição de nicho intra e interespecífica de períodos reprodutivos e não-reprodutivos.

A abordagem interanual de informações de forrageio de *S. dactylatra* foi essencial para identificar os padrões de forrageio à leste do arquipélago, o que foi relacionado com a dinâmica oceanográfica da região, cujas correntes ascendentes promovem áreas com recursos alimentares abundantes. Entretanto, também foi possível observar uma variação interanual na proximidade das áreas de forrageio e na dieta, indicando potenciais variações na distribuição e composição da comunidade de peixes epipelágicos no entorno do arquipélago. Dessa forma, o uso de dados de organismos que dependem de um recurso específico, contemplando variação interanual, permite obter respostas rápidas de consequências de alterações ambientais em pequena e grande escalas, considerando cenários atuais e futuros de mudanças climáticas.

Adicionalmente, através da obtenção de informações a respeito de estratégias de forrageio durante o período não-reprodutivo, também foi possível caracterizar a partição de nicho das duas espécies. Esse resultado indica que esse processo tem um importante papel para a coexistência de *S. dactylatra* e *S. sula* durante o ciclo reprodutivo de cada espécie e ao longo dos anos. Além disso, a combinação de informações de períodos reprodutivo e não-reprodutivo possibilitaram identificar uma potencial influência dominante de *S. dactylatra* sobre *S. sula*. Nesse sentido, considerando também o menor tamanho e massa corporal, *S. sula* aparenta variar seu nicho de acordo com a intensidade de exploração de recursos de seu conspecífico entre períodos reprodutivo e não-reprodutivo, ilustrando o conceito de relaxamento ecológico.

Por fim, o presente estudo evidenciou o potencial de aves marinhas como sentinelas de ambientes marinhos, indicando potenciais variações na distribuição e composição de suas presas através de suas estratégias de forrageio. Dessa forma, mesmo sendo consideradas oásis em um ambiente oligotrófico, ilhas oceânicas tropicais impõem condições limitantes para espécies que dependem dos mesmos recursos. Portanto, são importantes locais para ilustrar a partição de nicho entre espécies simpátricas, de modo a trazer luz sobre como essas espécies interagem no espaço e no tempo e como esses processos influenciam na manutenção da biodiversidade em ambientes marinhos.

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Ministério do Meio Ambiente - MMA

Instituto Chico Mendes de Conservação da Biodiversidade - ICMBio

Sistema de Autorização e Informação em Biodiversidade - SISBIO

Autorização para atividades com finalidade científica

Número: 64234-7	**Data da Emissão: 01/09/2022 09:59:54**	**Data da Revalidação*: 01/11/2022**

De acordo com o art. 28 da IN 03/2014, esta autorização tem prazo de validade equivalente ao previsto no cronograma de atividades do projeto, mas deverá ser revalidada anualmente mediante a apresentação do relatório de atividades a ser enviado por meio do Sisbio no prazo de até 30 dias a contar da data do aniversário de sua emissão.

Dados do titular

Nome: Guilherme Tavares Nunes	CPF: [redacted]
Título do Projeto: Uso do espaço e dos recursos por aves marinhas e costeiras no Brasil	
Nome da Instituição: UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL	CNPJ: 92.969.856/0001-98

Cronograma de atividades

#	Descrição da atividade	Início (mês/ano)	Fim (mês/ano)
1	Captura e marcação de indivíduos	07/2018	07/2023
2	Contagem de indivíduos e ninhos	07/2018	07/2023
3	Rastreamento remoto	07/2018	07/2023
4	Coleta de material biológico	07/2018	07/2023

Equipe

#	Nome	Função	CPF	Nacionalidade
1	Patricia Pereira Serafini	Colaboradora	[redacted]	Brasileira
2	PAULO HENRIQUE OTT	Colaborador	[redacted]	Brasileira
3	Bruno de Andrade Linhares	Colaborador	[redacted]	Brasileira
4	Patricia Luciano Mancini	Colaboradora	[redacted]	Brasileira
5	LEANDRO BUGONI	Colaborador	[redacted]	Brasileira
6	FERNANDO AZEVEDO FARIA	Colaborador	[redacted]	Brasileira
7	Júlia Jacoby de Souza	Colaboradora	[redacted]	Brasileira
8	Sophie Bertrand	Colaboradora		Estrangeira
9	FIORELLA ISABEL VILELA RIOS	Colaboradora	[redacted]	Estrangeira
10	CYNTHIA CAMPOLINA DE MELO VIANNA	Colaboradora	[redacted]	Brasileira
11	Luísa Bertolini	Pesquisadora	[redacted]	Brasileira

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Observações e ressalvas

1	A autorização não eximirá o pesquisador da necessidade de obter outras anuências, como: I) do proprietário, arrendatário, posseiro ou morador quando as atividades forem realizadas em área de domínio privado ou dentro dos limites de unidade de conservação federal cujo processo de regularização fundiária encontra-se em curso; II) da comunidade indígena envolvida, ouvido o órgão indigenista oficial, quando as atividades de pesquisa forem executadas em terra indígena; III) do Conselho de Defesa Nacional, quando as atividades de pesquisa forem executadas em área indispensável à segurança nacional; IV) da autoridade marítima, quando as atividades de pesquisa forem executadas em águas jurisdicionais brasileiras; V) do Departamento Nacional da Produção Mineral, quando a pesquisa visar a exploração de depósitos fossilíferos ou a extração de espécimes fósseis; VI) do órgão gestor da unidade de conservação estadual, distrital ou municipal, dentre outras.
2	Deve-se observar as as recomendações de prevenção contra a COVID-19 das autoridades sanitárias locais e das Unidades de Conservação a serem acessadas.
3	Esta autorização NÃO libera o uso da substância com potencial agrotóxico e/ou inseticida e NÃO exime o pesquisador titular e os membros de sua equipe da necessidade de atender às exigências e obter as autorizações previstas em outros instrumentos legais relativos ao registro de agrotóxicos (Lei nº 7.802, de 11 de julho de 1989, Decreto nº 4.074, de 4 de janeiro de 2002, entre outros).
4	Esta autorização NÃO libera o uso da substância com potencial agrotóxico e/ou inseticida e NÃO exime o pesquisador titular e os membros de sua equipe da necessidade de atender às exigências e obter as autorizações previstas em outros instrumentos legais relativos ao registro de agrotóxicos (Lei nº 7.802, de 11 de julho de 1989, Decreto nº 4.074, de 4 de janeiro de 2002, entre outros)
5	Este documento somente poderá ser utilizado para os fins previstos na Instrução Normativa ICMBio nº 03/2014 ou na Instrução Normativa ICMBio nº 10/2010, no que especifica esta Autorização, não podendo ser utilizado para fins comerciais, industriais ou esportivos. O material biológico coletado deverá ser utilizado para atividades científicas ou didáticas no âmbito do ensino superior.
6	As atividades de campo exercidas por pessoa natural ou jurídica estrangeira, em todo o território nacional, que impliquem o deslocamento de recursos humanos e materiais, tendo por objeto coletar dados, materiais, espécimes biológicos e minerais, peças integrantes da cultura nativa e cultura popular, presente e passada, obtidos por meio de recursos e técnicas que se destinem ao estudo, à difusão ou à pesquisa, estão sujeitas a autorização do Ministério de Ciência e Tecnologia.
7	Este documento não dispensa o cumprimento da legislação que dispõe sobre acesso a componente do patrimônio genético existente no território nacional, na plataforma continental e na zona econômica exclusiva, ou ao conhecimento tradicional associado ao patrimônio genético, para fins de pesquisa científica, bioprospecção e desenvolvimento tecnológico. Veja maiores informações em www.mma.gov.br/cgen.
8	O titular de licença ou autorização e os membros da sua equipe deverão optar por métodos de coleta e instrumentos de captura direcionados, sempre que possível, ao grupo taxonômico de interesse, evitando a morte ou dano significativo a outros grupos; e empregar esforço de coleta ou captura que não comprometa a viabilidade de populações do grupo taxonômico de interesse em condição in situ.
9	Esta autorização NÃO exime o pesquisador titular e os membros de sua equipe da necessidade de obter as anuências previstas em outros instrumentos legais, bem como do consentimento do responsável pela área, pública ou privada, onde será realizada a atividade, inclusive do órgão gestor de terra indígena (FUNAI), da unidade de conservação estadual, distrital ou municipal, ou do proprietário, arrendatário, posseiro ou morador de área dentro dos limites de unidade de conservação federal cujo processo de regularização fundiária encontra-se em curso.
10	Em caso de pesquisa em UNIDADE DE CONSERVAÇÃO, o pesquisador titular desta autorização deverá contactar a administração da unidade a fim de CONFIRMAR AS DATAS das expedições, as condições para realização das coletas e de uso da infraestrutura da unidade.
11	O titular de autorização ou de licença permanente, assim como os membros de sua equipe, quando da violação da legislação vigente, ou quando da inadequação, omissão ou falsa descrição de informações relevantes que subsidiaram a expedição do ato, poderá, mediante decisão motivada, ter a autorização ou licença suspensa ou revogada pelo ICMBio, nos termos da legislação brasileira em vigor.

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Outras ressalvas

1		APA Baleia Franca
2		APA Cananéia-Iguape-Peruíbe
3		MONA Arquipélago das Ilhas Cagarras
4		PARNA da Lagoa do Peixe
5		RESEX Arraial do Cabo
6	1. As atividades na ilha de Santa Bárbara dependem de autorização específica da Marinha do Brasil. 2. Antes de realizar os trabalhos de campo os pesquisadores deverão entrar em contato pelo e-mail: pesquisa.parnaabrolhos@icmbio.gov.br, com no mínimo 25 dias de antecedência, para compatibilização do cronograma da pesquisa com as demais atividades de uso público, monitoramento e pesquisa desenvolvidas na UC, conforme o caso. 3. Os pesquisadores devem enviar ao Parque cópia das publicações resultantes da pesquisa e, se possível, agendar uma breve apresentação no Centro de Visitantes para divulgação dos resultados da pesquisa à equipe do NGI Abrolhos e comunidades locais. 4. Deve-se atentar às restrições federais, estaduais e municipais para coletas realizadas durante a pandemia de Covid-19.	PARNA Marinho dos Abrolhos
7	A pesquisadora estrangeira Sophie Bertrand é portadora de visto permanente no Brasil; enquanto a pesquisadora estrangeira Fiorella Isabel Vilela Rios possui vínculo junto a programa de bolsas ou auxílio à pesquisa patrocinado pela CAPES. Portanto, estão dispensadas de autorização do Ministério da Ciência, Tecnologia e Inovação, conforme definido no ?item? 56, da Portaria MCT nº 826/2008, e no inciso II, art. 5º da Resolução Normativa nº 20/2017, do Conselho Nacional de Imigração - CNig.	COINF
8	As expedições deverão ser combinadas com a equipe técnica da Unidade de Conservação, tendo em vista que o planejamento para a ocupação da estação científica é bianual e o número de pessoas por expedição é controlado, sendo as vagas distribuídas de acordo com as sazonalidades ou licenças já expedidas. Todas as atividades de campo serão acompanhadas por um responsável designado pela UC, que poderá ser a Chefe da Unidade, um Analista Ambiental do ICMBio ou prestador de serviço. O responsável poderá, justificadamente, interromper ou suspender a expedição, caso constate indícios de descumprimento da legislação ambiental federal, danos à Unidade de Conservação ou desenvolvimento das atividades em desacordo com a licença de pesquisa emitida via SISBIO.	REBIO Atol das Rocas
9	As saídas de campo devem ser previamente comunicadas a equipe da Reserva com antecedência mínima de 24h, por meio do email rebio.arvoredo@icmbio.gov.br. NÃO SERÃO AUTORIZADAS SAÍDAS COMUNICADAS COM TEMPO INFERIOR A 24H DE ANTECEDÊNCIA. No email deverão constar as seguintes informações: (1) nº da autorização SISBIO; (2) nome do titular da autorização; (3) data da saída; (4) horário previsto de saída e retorno; (5) embarcação a ser utilizada; (6) empresa responsável pela operação de mar; (7) identificação da equipe de pesquisa a bordo, com respectivos CPF; (8) identificação do pesquisador responsável pela saída. Para pesquisas que envolvam mergulho autônomo é necessário que os pesquisadores possuam certificação de mergulho avançado para realização dos trabalhos de campo e que o nº da certificação seja informado no email. O responsável pela saída deverá portar cópia da autorização a bordo. Caso seja necessário o desembarque nas áreas terrestres é necessário o acompanhamento de analistas ambientais da Reserva e, portanto, deverão ser previamente agendadas com a equipe da UC de acordo com disponibilidade de agenda. Para as pesquisas que necessitarem de apoio das embarcações da Reserva, os titulares das mesmas deverão entrar em contato prévio com a equipe da UC, para avaliação de disponibilidade e logística.	REBIO Marinha do Arvoredo

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Nome da Instituição: UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL	CNPJ: 92.969.856/0001-98

Outras ressalvas

10	Comunicar a gestão da unidade previamente para o acesso ao Refúgio de Vida Silvestre da Ilha dos Lobos. A fim de compormos um banco de pesquisas da UC, solicitamos que as publicações científicas originária da pesquisa sejam enviadas para o e-mail da unidade (revisilhadoslobos@icmbio.gov.br), bem como as imagens que poderão ser utilizadas em ações educacionais e institucionais com o devido registro dos seus créditos.	REVIS Ilha dos Lobos
11	NGI ICMBio Alcatrazes: Ressalva 1) O coordenador do projeto deverá entrar em contato com a gestão da UC antes do inicio de qualquer atividade de campo, visando a construção de um cronograma de atividades em conjunto, que deverão ser obrigatoriamente acompanhadas por um integrante do ICMBio Alcatrazes. 2) Encaminhar às unidades de conservação do ICMBio Alcatrazes, qualquer publicação e/ou divulgação oriunda deste trabalho.	REVIS Arquipélago de Alcatrazes
12	O desembarque na ilhas é restrito a atividades de pesquisa, monitoramento de indicadores, atividades especiais de gestão ou eventos de comunicação/divulgação selecionados, logo as excursões a UC DEVEM ser AGENDADAS/INFORMADAS ao NGI Matinhos com antecedência, sem exceção.	PARNA Marinho das Ilhas dos Currais
13	O pesquisador deverá entrar em contato via e-mail (pesquisaparnamarfn@gmail.com) e apresentar cronograma de atividades no escritório do ICMBio antes do início das coletas em Fernando de Noronha. O pesquisador deverá encaminhar ao ICMBio em Fernando de Noronha cópia digital das publicações resultantes do Estudo.	CR 6 Cabedelo-PB
14	Quando o pesquisador ou equipe vier a Fernando de Noronha, o pesquisador deverá entrar em contato através do email: pesquisa.noronha@icmbio.gov.br informando a data das expedições a Fernando de Noronha e deverá comparecer à sede do ICMBio em Fernando de Noronha para entregar cronograma das atividades antes do início dos trabalhos de campo em FN. Recomendamos que o pesquisador acesse o site https://www.parnanoronha.com.br/pesquisa, se informe e baixe o manual do pesquisador antes de contatar a unidade. Qualquer intercorrência com os animais capturados devem ser comunicadas ao ICMBio e devem constar de relatório da pesquisa com bibliografia indicando a viabilidade da técnica, bem como das taxas de mortalidade observada.	APA Fernando de Noronha
15	Quando o pesquisador ou equipe vier a Fernando de Noronha, o pesquisador deverá entrar em contato através do email: pesquisa.noronha@icmbio.gov.br informando a data das expedições a Fernando de Noronha e deverá comparecer à sede do ICMBio em Fernando de Noronha para entregar cronograma das atividades antes do início dos trabalhos de campo em FN. Recomendamos que o pesquisador acesse o site https://www.parnanoronha.com.br/pesquisa, se informe e baixe o manual do pesquisador antes de contatar a unidade. Qualquer intercorrência com os animais capturados devem ser comunicadas ao ICMBio e devem constar de relatório da pesquisa com bibliografia indicando a viabilidade da técnica, bem como das taxas de mortalidade observada.	PARNA Marinho de Fernando de Noronha

Locais onde as atividades de campo serão executadas

#	**Descrição do local**	**Município-UF**	**Bioma**	**Caverna?**	**Tipo**
1	Parque Nacional Marinho das Ilhas dos Currais	PR	Marinho	Não	Dentro de UC Federal
2	Área de Proteção Ambiental de Cananéia-Iguape-Peruíbe	SP	Marinho	Não	Dentro de UC Federal

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Locais onde as atividades de campo serão executadas

#	Descrição do local	Município-UF	Bioma	Caverna?	Tipo
3	Parque Nacional Marinho de Fernando de Noronha	PE	Marinho	Não	Dentro de UC Federal
4	Reserva Biológica do Atol das Rocas	RN	Marinho	Não	Dentro de UC Federal
5	Área de Proteção Ambiental de Fernando de Noronha - Rocas - São Pedro e São Paulo	PE	Marinho	Não	Dentro de UC Federal
6	Reserva Biológica Marinha do Arvoredo	SC	Marinho	Não	Dentro de UC Federal
7	Parque Nacional da Lagoa do Peixe	RS	Marinho	Não	Dentro de UC Federal
8	Refúgio de Vida Silvestre Ilha dos Lobos	RS	Marinho	Não	Dentro de UC Federal
9	Área de Proteção Ambiental da Baleia Franca	SC	Marinho	Não	Dentro de UC Federal
10	Ambientes costeiros	Tavares-RS	Marinho	Não	Fora de UC Federal
11	Ambientes costeiros	Tramandaí-RS	Marinho	Não	Fora de UC Federal
12	Ambientes costeiros	Torres-RS	Marinho	Não	Fora de UC Federal
13	Ambientes costeiros	Mostardas-RS	Marinho	Não	Fora de UC Federal
14	Reserva Extrativista Arraial do Cabo	RJ	Marinho	Não	Dentro de UC Federal
15	Refúgio de Vida Silvestre do Arquipélago de Alcatrazes	SP	Marinho	Não	Dentro de UC Federal
16		BA	Marinho	Não	Fora de UC Federal
17	Monumento Natural Arquipélago das Ilhas Cagarras	RJ	Marinho	Não	Dentro de UC Federal
18	Parque Nacional Marinho dos Abrolhos	BA	Marinho	Não	Dentro de UC Federal
19	Ambientes costeiros	Imbé-RS	Marinho	Não	Fora de UC Federal

Atividades

#	Atividade	Grupo de Atividade
1	Coleta/transporte de amostras biológicas in situ	Outras atividades
2	Coleta/transporte de amostras biológicas in situ	Fora de UC Federal
3	Coleta/transporte de amostras biológicas in situ	Dentro de UC Federal
4	Captura de animais silvestres in situ	Fora de UC Federal
5	Captura de animais silvestres in situ	Dentro de UC Federal
6	Captura de animais silvestres in situ	Outras atividades
7	Observação e gravação de imagem ou som de táxon em UC federal	Dentro de UC Federal

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Autorização para atividades com finalidade científica

Número: 64234-7	**Data da Emissão: 01/09/2022 09:59:54**	**Data da Revalidação*: 01/11/2022**

De acordo com o art. 28 da IN 03/2014, esta autorização tem prazo de validade equivalente ao previsto no cronograma de atividades do projeto, mas deverá ser revalidada anualmente mediante a apresentação do relatório de atividades a ser enviado por meio do Sisbio no prazo de até 30 dias a contar da data do aniversário de sua emissão.

Dados do titular

Nome: Guilherme Tavares Nunes	CPF:
Título do Projeto: Uso do espaço e dos recursos por aves marinhas e costeiras no Brasil	
Nome da Instituição: UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL	CNPJ: 92.969.856/0001-98

Atividades

#	Atividade	Grupo de Atividade
8	Marcação de animais silvestres in situ	Outras atividades
9	Marcação de animais silvestres in situ	Dentro de UC Federal
10	Marcação de animais silvestres in situ	Fora de UC Federal
11	Levantamento de dados abióticos em UC federal	Dentro de UC Federal
12	Pesquisa em unidade de conservação federal	Outras atividades

Atividades X Táxons

#	Atividade	Táxon	Qtde.
1	Coleta/transporte de amostras biológicas in situ	Procellariiformes	-
2	Captura de animais silvestres in situ	Procellariiformes	-
3	Observação e gravação de imagem ou som de táxon em UC federal	Procellariiformes	-
4	Marcação de animais silvestres in situ	Procellariiformes	-
5	Coleta/transporte de amostras biológicas in situ	Charadriiformes	-
6	Captura de animais silvestres in situ	Charadriiformes	-
7	Marcação de animais silvestres in situ	Charadriiformes	-
8	Observação e gravação de imagem ou som de táxon em UC federal	Charadriiformes	-
9	Coleta/transporte de amostras biológicas in situ	Pelecaniformes	-
10	Captura de animais silvestres in situ	Pelecaniformes	-
11	Observação e gravação de imagem ou som de táxon em UC federal	Pelecaniformes	-
12	Marcação de animais silvestres in situ	Pelecaniformes	-
13	Observação e gravação de imagem ou som de táxon em UC federal	Sphenisciformes	-
14	Captura de animais silvestres in situ	Sphenisciformes	-
15	Marcação de animais silvestres in situ	Sphenisciformes	-
16	Coleta/transporte de amostras biológicas in situ	Sphenisciformes	-
17	Captura de animais silvestres in situ	Phaethontiformes	-
18	Coleta/transporte de amostras biológicas in situ	Phaethontiformes	-
19	Observação e gravação de imagem ou som de táxon em UC federal	Phaethontiformes	-
20	Marcação de animais silvestres in situ	Phaethontiformes	-
21	Coleta/transporte de amostras biológicas in situ	Suliformes	-

Autorização para atividades com finalidade científica

Número: 64234-7	**Data da Emissão: 01/09/2022 09:59:54**	**Data da Revalidação*: 01/11/2022**

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Dados do titular

Nome: Guilherme Tavares Nunes	CPF: [redacted]
Título do Projeto: Uso do espaço e dos recursos por aves marinhas e costeiras no Brasil	
Nome da Instituição: UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL	CNPJ: 92.969.856/0001-98

Atividades X Táxons

#	Atividade	Táxon	Qtde.
22	Captura de animais silvestres in situ	Suliformes	-
23	Observação e gravação de imagem ou som de táxon em UC federal	Suliformes	-
24	Marcação de animais silvestres in situ	Suliformes	-

A quantidade prevista só é obrigatória para atividades do tipo "Coleta/transporte de espécimes da fauna silvestre in situ". Essa quantidade abrange uma porção territorial mínima, que pode ser uma Unidade de Conservação Federal ou um Município.

A quantidade significa: por espécie X localidade X ano.

Materiais e Métodos

#	Tipo de Método (Grupo taxonômico)	Materiais
1	Amostras biológicas (Aves)	Ectoparasita, Penas, Fezes, Sangue, Animal encontrado morto ou partes (carcaça)/osso/pele, Fragmento de tecido/órgão, Regurgitação/conteúdo estomacal
2	Método de captura/coleta (Aves)	Armadilha fotográfica, Vara com laço, Puçá, Rede de solo com elástico, Rede de neblina, Bioacústica, Tapete
3	Método de marcação (Aves)	Anilha, Anilha metálica (padrão CEMAVE), Rádio transmissor externo, Anilha de inox, Anilhas coloridas, Corantes

Destino do material biológico coletado

#	Nome local destino	Tipo destino
1	UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL	Coleção

Autorização para atividades com finalidade científica

Número: 64234-7	**Data da Emissão: 01/09/2022 09:59:54**	**Data da Revalidação*: 01/11/2022**

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Dados do titular

Nome: Guilherme Tavares Nunes	CPF: [redacted]
Título do Projeto: Uso do espaço e dos recursos por aves marinhas e costeiras no Brasil	
Nome da Instituição: UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL	CNPJ: 92.969.856/0001-98

Registro de coleta imprevista de material biológico

De acordo com a Instrução Normativa nº03/2014, a coleta imprevista de material biológico ou de substrato não contemplado na autorização ou na licença permanente deverá ser anotada na mesma, em campo específico, por ocasião da coleta, devendo esta coleta imprevista ser comunicada por meio do relatório de atividades. O transporte do material biológico ou do substrato deverá ser acompanhado da autorização ou da licença permanente com a devida anotação. O material biológico coletado de forma imprevista, deverá ser destinado à instituição científica e, depositado, preferencialmente, em coleção biológica científica registrada no Cadastro Nacional de Coleções Biológicas (CCBIO).

Táxon*	**Qtde.**	**Tipo de Amostra**	**Qtde.**	**Data**

* Identificar o espécime do nível taxonômico possível.

U F R G S
UNIVERSIDADE FEDERAL
DO RIO GRANDE DO SUL

PRÓ-REITORIA DE PESQUISA
Comissão De Ética No Uso De Animais

CEUA
UFRGS

CARTA DE APROVAÇÃO

Comissão De Ética No Uso De Animais analisou o projeto:

Número: 37905
Título: Uso do espaço e dos recursos por aves marinhas e costeiras

Vigência: 01/10/2019 à 31/12/2025

Pesquisadores:

Equipe UFRGS:

Guilherme Tavares Nunes - coordenador desde 01/10/2019

Equipe Externa:

Leandro Bugoni - pesquisador desde 01/10/2019
Márcio Amorim Efe - pesquisador desde 01/10/2019
Patrícia Pereira Serafini - pesquisador desde 01/10/2019
Sophie Bertrand - pesquisador desde 01/10/2019

Comissão De Ética No Uso De Animais aprovou o mesmo , em reunião realizada em 06/01/2020 - Plenarinho - Andar Térreo do Prédio da Reitoria - Campus Centro/UFRGS - AV. Paulo Gama/ RS, em seus aspectos éticos e metodológicos, animais de vida livre, 500 da ordem Procellariiformes, 60da ordem Sphenisciformes, 300 da ordem Phaethontiformes, 890 da ordem Suliformes e 4.530 da ordem Charadriiformes provenientes de 16 unidades de Conservação federais marinhas e costeiras,e também em áreas sem proteção legal que possuam relevância para a proteção das aves marinhas e costeiras no Brasil, de acordo com os preceitos das Diretrizes e Normas Nacionais e Internacionais, especialmente a Lei 11.794 de 08 de novembro de 2008, o Decreto 6899 de 15 de julho de 2009, e as normas editadas pelo Conselho Nacional de Controle da Experimentação Animal (CONCEA), que disciplinam a produção, manutenção e/ou utilização de animais do filo Chordata, subfilo Vertebrata (exceto o homem) em atividade de ensino ou pesquisa.

Porto Alegre, Segunda-Feira, 2 de Março de 2020

ALEXANDRE TAVARES DUARTE DE OLIVEIRA
Coordenador da comissão de ética

Ministério do Meio Ambiente
CONSELHO DE GESTÃO DO PATRIMÔNIO GENÉTICO

SISTEMA NACIONAL DE GESTÃO DO PATRIMÔNIO GENÉTICO E DO CONHECIMENTO TRADICIONAL ASSOCIADO

Comprovante de Cadastro de Acesso

Cadastro nº A7D12B8

A atividade de acesso ao Patrimônio Genético, nos termos abaixo resumida, foi cadastrada no SisGen, em atendimento ao previsto na Lei nº 13.123/2015 e seus regulamentos.

Número do cadastro:	**A7D12B8**
Usuário:	**Guilherme Tavares Nunes**
CPF/CNPJ:	[redacted]
Objeto do Acesso:	**Patrimônio Genético**
Finalidade do Acesso:	**Pesquisa**

Espécie

Sula sula

Sula dactylatra

Título da Atividade:	**Variações intra e interespecíficas nas estratégias de forrageio de Sula spp. (Suliformes: Sulidae) no oceano Atlântico tropical**

Equipe

Guilherme Tavares Nunes	**UFRGS**
Júlia Jacoby de Souza	**UFRGS**

Parceiras Nacionais

94.877.586/0001-10 / Universidade Federal do Rio Grande - FURG

Parceiras no Exterior

Institut Recherche Pour Le Développement

Resultados Obtidos

Divulgação de resultados em meios científicos ou de comunicação

Identificação do meio onde foi divulgado: **Periódicos científicos, e resumos de congress**

Data do Cadastro: **21/03/2024 01:26:56**

Situação do Cadastro: **Concluído**

Conselho de Gestão do Patrimônio Genético
Situação cadastral conforme consulta ao SisGen em **1:27** de **21/03/2024**.

SISTEMA NACIONAL DE GESTÃO
DO PATRIMÔNIO GENÉTICO
E DO CONHECIMENTO TRADICIONAL
ASSOCIADO - **SISGEN**