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BRIEF REPORT

Analysis of free-living seabirds from Brazil as potential hosts of *Toxoplasma gondii* and serological investigation for antibodies against *Leptospira* spp.

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Abstract

Dispersal patterns of zoonotic pathogens can be strongly influenced by mobility and contact among hosts. *Toxoplasma gondii* infection has been documented in many avian species, however, there is little information regarding free-living seabird populations. *Leptospira* can infect domestic and wild animals, with birds being potential carriers of the bacteria. The continental shelf of the southwestern Atlantic Ocean is a foraging area for seabirds that breed locally, as well as migratory seabirds wintering in the area, which may come into contact with each other in prey aggregation areas and contribute to *T. gondii* and *Leptospira* spread. Therefore, this study aimed to investigate the prevalence of two important zoonotic pathogens in free-living seabirds. Blood samples were collected from 322 birds of three local breeders (*Phaethon aethereus*, *Sula leucogaster* and *S. dactylatra*) in the eastern coast of Brazil (Abrolhos Archipelago), and two migratory species using the area during the pre-laying (*Pterodroma arminjoniana*) and the non-breeding periods (*Thalassarche chlororhynchos*). Serological agglutination tests for detection of anti-*Toxoplasma gondii* and anti-*Leptospira* spp. antibodies were performed. None of the seabirds in this study was seroreactive to *Leptospira* spp., whereas 34.5% ($n = 111$) of the animals presented antibodies anti-*T. gondii*. Antibody titers in seropositive birds ranged from 10 to 640. There were seropositive birds in all sampled localities. This study provides the first records for *P. arminjoniana* and *T. chlororhynchos* as seropositive to *T. gondii*, suggesting their potential role as sentinels for the environmental contamination by *T. gondii* and also *T. gondii* infection. These findings indicate the circulation of the parasite in the Brazilian coastal and oceanic regions, probably due to the ingestion of *T. gondii* oocysts by birds, the epidemiological involvement of migratory birds as hosts of pathogens, as well as the role of the historical introduction of invasive vertebrates on Brazilian islands. Therefore, due to the serological evidence of infection, the dynamics of toxoplasmosis in seabirds, regarding their susceptibility towards the disease and the possible anthropogenic influence need to be better understood for the colonies to be included in the wildlife cycle of *T. gondii*.

Keywords Avian diseases · Breeding seabirds · One Health · Phaethontiformes · Procellariiformes · Protozoan · Suliformes · Wildlife

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Statement
All methods in this study were carried out in accordance with the relevant institutional guidelines and regulations confirming the study is reported in accordance with ARRIVE guidelines.

Extended author information available on the last page of the article

Introduction

The importance of disease dispersal by seabirds extends beyond their foraging behavior when considering the One Health approach. By promoting transdisciplinary collaborations and integrative research, the One Health framework helps raise awareness of zoonotic disease and facilitates effective prevention and control strategies. Being at high positions in the trophic web, seabirds have the potential to reflect processes that affect their prey at lower trophic levels and are regarded as sentinels of ocean health (Furness 2003; Cardoso et al. 2014). Therefore, they can be useful indicators of altered ecological processes and environmental conditions and could be used as a source of key information on marine ecosystem health (Parsons et al. 2008; Grimaldi et al. 2015; Graham et al. 2018). Additionally, seabirds are highly mobile organisms (Fijn et al. 2013), frequently moving between breeding areas on islands and distant wintering grounds (Schreiber and Burger 2001). Consequently, their foraging characteristics and mobility enable them to function as hosts for the dispersal of zoonotic microorganisms. Seabirds also gather in heterospecific flocks in foraging areas (Goyert 2015; Ward and Webster 2016; Monier 2024). Usually, zoonotic pathogens demonstrate low host specificity, facilitating their spread in environments where multiple species coexist (Estrada-Peña et al. 2014; Khan et al. 2019).

Toxoplasma gondii, a worldwide distributed zoonotic parasite, infects nearly all warm-blooded animals and causes acute disease in wild birds. However, there is limited information on toxoplasmosis in seabird populations, particularly among free-living seabirds in Brazil (Dubey 2010; Vielmo et al. 2019; Dubey et al. 2021). Another possible zoonotic pathogen harbored by seabirds is a bacterial spirochete of the genus *Leptospira*. This infection is widespread in domestic and wild animals from tropical regions and is transmissible to humans (WOAH 2021). Birds are considered to present a refractory nature to leptospiral infections; however, recent studies are challenging this view, with reports of seroprevalence of anti-*Leptospira* antibodies (Vieira et al. 2018; Acosta et al. 2019).

Invasive species are one of the main threats posed to seabirds, given their ability to degrade habitats, predate adults and chicks, and spread pathogens to populations that interact with them (Gennari et al. 2016a; Dias et al. 2019). In Brazilian archipelagos used by seabirds for nesting, the occurrence of invasive mammals, such as domestic cats and rodents, exacerbates the problem of zoonotic pathogen dispersal (Alves 1998; Campolina 2013; Linhares et al. 2023). As hosts of *T. gondii* and *Leptospira* spp., cats and rodents, respectively, could be key factors in the emergence of both pathogens on islands, enabling the persistence of the bacteria and protozoan even after the eradication of the intruders, along with the risk of infection for birds. Previous epidemiological studies on toxoplasmosis and leptospirosis in wild hosts and humans from island and coastal areas are scarce, with reports from Bahia indicating antibodies against *T. gondii* detected in 34.8% of seabirds (Gennari et al. 2016a) and seroprevalence rates for specific IgG anti-*T. gondii* antibodies of 51% (362) and 93% (219) among mothers and neonates, respectively (Avelar et al. 2017).

In this context, this study aims to investigate the exposure of seabirds to important zoonotic pathogens, *T. gondii* and *Leptospira* spp., in free-living seabirds sharing the same foraging area around the Doce River mouth. We have tested the presence of *T. gondii* and *Leptospira* spp. antibodies in three resident free-living seabird species from colonies located in the Abrolhos Archipelago (i.e. *Sula leucogaster*, *S. dactylatra*, and *Phaethon aethereus*), and two migratory species that use the area during the pre-laying period (*Pterodroma arminjoniana*) and the non-breeding period (*Thalassarche chlororhynchos*). This study investigates evidence of infection with *Leptospira* spp. and *T. gondii* in seabirds, focusing on animals coexisting with human interactions and invasive species in Brazilian waters.

Material and methods

This study adopted the Ethical Principles in Animal Research according to Brazilian College of Animal Experimentation and was approved by the Ethical Committee for Animal Research of the Faculty of Veterinary Medicine, University of São Paulo (Protocol No. 9959300821); Animal Use Ethical Committee at FURG (P040/2018) and Animal Use Ethical Committee at UFRGS (37905) with authorization of the Chico Mendes Institute for Biodiversity Conservation, Brazil (Sisbio No. 64381–2; 64,234–9). No anesthesia was used, and no animals were sacrificed during the study.

Study area, sampling and parameters

Resident seabirds breed in the Abrolhos Archipelago, while migrants travel from tropical oceanic archipelagos like Trindade Island or sub-Antarctic regions like Tristan da Cunha and Gough Archipelago. Seabirds breeding in Abrolhos, such as *P. aethereus, S. leucogaster*, and *S. dactylatra*, use the archipelago for breeding and the surrounding continental shelf for foraging, overlapping in space (Nunes et al. 2022). The same area is used by *P. arminjoniana* during the pre-laying period (Leal et al. 2017) and by *T. chlororhynchos* during the non-breeding period (Gabani and Bugoni unpub. data).

The Abrolhos Archipelago is in the northeastern region of Brazil, composed by five small islands ~ 70 km away from the coast, with the largest (Santa Barbara, ~1.5 km in length) managed by the Brazilian Navy, and the remaining areas by the Abrolhos Marine National Park (ICMBio), which also protects ~90,000 ha of marine environments (IBAMA-FUNATURA 1991). Santa Barbara, Trindade and Tristan da Cunha, hold a human population of military or local residents and research teams that visits the islands (Leal and Bouchet 1991; Angel and Cooper 2006; Alves 1998; Campolina 2013). The marine protected area holds colonies of seven seabird species, including *P. aethereus*, *S. leucogaster* and *S. dactylatra*, which breed in the Abrolhos Archipelago. Trindade Island (20°30′S–29°19′W) is about 1200 km eastward of Abrolhos, and 1140 km away of the South American coast at the eastern end of the Vitória-Trindade Seamount Chain (Barth 1958). It is a volcanic island, with an area of 8 km^2, rocky terrain and a narrow shelf of only 32 km^2, surrounded by deep waters up to ~5500 m depth (Leal and Bouchet 1991), holding the main colony of *P. arminjoniana* globally (Leal et al. 2017).

Samples from *S. dactylatra*, *S. leucogaster* and *P. aethereus* were obtained in Abrolhos, on the Islands of Santa Bárbara (17°57′45.5″S and 38°42′06.8″W) and Redonda (17°57′57.8′S and 38°42′35.2″W). Samples from *P. arminjoniana* were collected on Trindade Island (20°30′Sand 29°19′W), and samples from *T. chlororhynchos* were collected at sea along the Brazilian coast (Fig. 1). The island of Santa Barbara has historically harbored a population of freely roaming domestic cats. Concurrently with Redonda, it housed exotic rodents until the year 2023, when an eradication project onsite was successful. The island of Trindade exclusively harbors exotic house mice *Mus musculus*, and there are no ongoing mid-term eradication projects in progress (Alves 1998; Campolina 2013).

Serum samples were collected on Abrolhos from 2018 to 2022, in which two campaigns per year were carried out, one in the first semester and another in the second semester, aiming to obtain a maximum of 20 specimens of each species by campaign, with exception of *T. chlororhynchos*, with 10 specimens, according with the official license. Exceptionally, in 2020, samples were collected only in the first semester due to the COVID-19 pandemic. Adult birds nesting on islands were captured directly from the nest, manually contained, and their blood was sampled by puncturing the tarsal vein. Each bird was individually identified with metal rings, briefly monitored, and then released, with minimal handling time, according to previously described protocols (Clark et al. 2009; Serafini and Lugarini 2014). Albatrosses were captured at sea with nets, as described by Bugoni et al. (2008), and sampled following the same method as described above. The serum samples were kept at − 20 °C until analysis.

Serological analysis

Immunoglobulin G (IgG) antibodies anti-*T. gondii* were detected using the modified agglutination test (MAT-Toxoplasma) (Dubey and Desmonts 1987), the most sensitive test (sensitivity = 76% and specificity = 68%) for detecting *T. gondii* antibodies in birds serum samples (Dubey et al. 2010; Casartelli-Alves et al. 2014; Dubey et al. 2016). The serum samples were initially screened at 1:5 dilution and the positive samples were end-titrated. Positive and

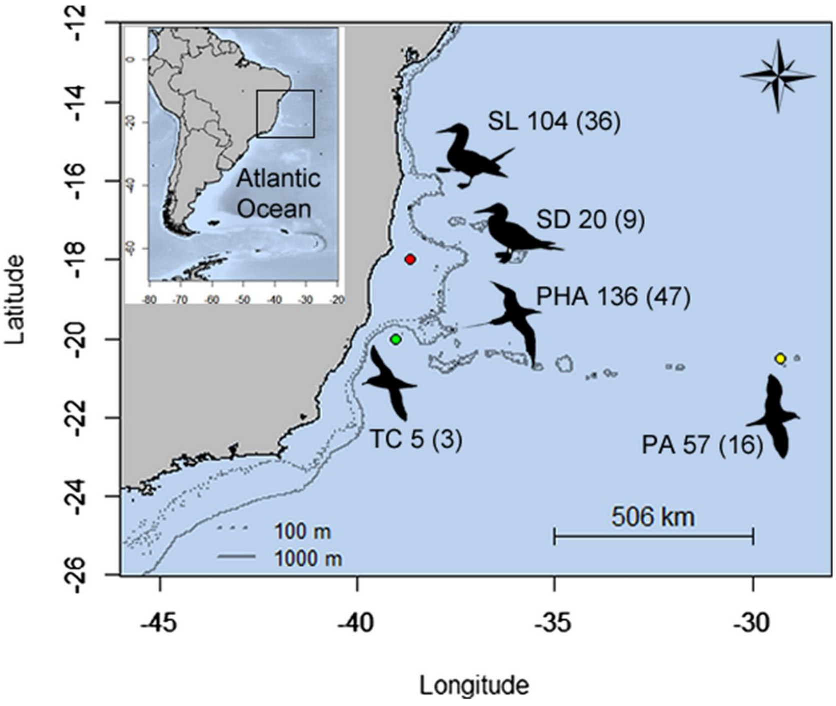

Figure 1 Spatial distribution of sampling sites in the southwestern Atlantic Ocean: Abrolhos Archipelago (red), Trindade Island (yellow) and offshore waters (green). SL = *Sula leucogaster*, SD = *Sula dactylatra*, PA = *Phaethon aethereus*, TC = *Thalassarche chlororhynchos*, PA = *Pterodroma arminjoniana*. Numbers represent the number of individuals sampled, while the number of positive samples for *Toxoplasma gondii* are in parenthesis. The Fig. 1 was made in R environment using 'marmap' package. The silhouettes were made by GC, using GIMP version 2.10.36 (https://www.gimp.org/downloads/)

negative serum samples from chickens were used as controls. Detection of anti-*Leptospira* spp. IgG antibodies was performed using the microscopic agglutination test (MAT-Leptospira), in accordance with the standard procedure recommended by the World Organization for Animal Health (WOAH, former OIE) (WOAH 2021), using the 23 serovars listed in supplementary material. The serum samples were first tested with the whole antigen collection, at a dilution of 1:100, and then titrated with the reacting antigens in a double dilution series. The titer for positive reactions was the reciprocal of the highest serum dilution in serum antigen mixtures that showed 50% agglutinated leptospires per microscopic field. The two tests were conducted by the Department of Preventive Veterinary Medicine and Animal Health at the University of São Paulo.

Statistical analysis

We opted to conduct a non-parametric statistical assessment instead of developing linear models, due to small sample sizes and the presence of overdispersion in the data. We used the Shapiro-Wilk test to assess the normality of titration results and employed the Kruskal-Wallis test and pairwise Mann-Whitney U tests, with Bonferroni correction, to compare antibody titrations among species. To compare titrations between colonies (Trindade and Abrolhos), we used a Mann-Whitney U test (Legendre and Legendre 2012). In both cases we considered non-seroreactive titrations as zero and analysis was performed using R Environment (R Core Team 2020). All graphs were built in R environment (R Core Team 2020), map (Fig. 1) in 'marmap' package (Pante and Simon-Bouhet 2013), and barplot (Suppl. 2) in 'ggplot 2' package (Wickham 2016).

Table 1 Results of the modified agglutination test (MAT) for anti-*Toxoplasma gondii* antibodies in five free-living seabirds sampled in the southwestern Atlantic Ocean

Seabird species	Tested	Positives*	%	Antibody titer (no. of birds)
Phaethon aethereus	136	47	34.5	10 (14); 20 (11); 40 (10); 80 (8); 160 (2); 320 (2)
Pterodroma arminjoniana	57	16	28	10 (5); 20 (8); 40 (2); 80 (1)
Sula dactylatra	20	9	45	10 (3); 40 (1); 80 (2); 160 (1); 320 (1); 640 (1)
Sula leucogaster	104	36	34.6	10 (8); 20 (5); 40 (8); 80 (9); 160 (1); 320 (1); 640 (4)
Thalassarche chlororhynchos	5	3	60	20 (2); 40 (1)
Total	**322**	**111**	**34.5**	**10 (30); 20 (26); 40 (22); 80 (20); 160 (4); 320 (4); 640 (5)**

*cut-off = 1:5

Results and discussion

A total of 322 seabirds from five species were tested (Table 1). Blood samples were collected from a total of 20 *S. dactylatra* (all from Santa Barbara Island), 104 *S. leucogaster* (80 from Santa Barbara and 24 from Redonda Island), 136 *P. aethereus* (100 from Santa Barbara and 36 from Redonda Island), 57 *P. arminjoniana*, and five *T. chlororhynchos*. A visual inspection of the birds revealed no apparent signs of illness or injury. None of the seabirds in this study was seroreactive to anti-*Leptospira* spp. antibodies.

Antibodies anti-*T. gondii* were detected in 111 (34.5%) individuals, with titers ranging from 10 to 640 (Table 1, Fig. 1). From Abrolhos, 260 seabirds were tested and 96 (36.9%) presented *T. gondii* antibodies [47 (34.5%) *P. aethereus*, 36 (34.6%) *S. leucogaster*, 9 (45.0%) *S. dactylatra*]. From Trindade, 16 of the 57 *P. arminjoniana* (28.0%) examined had anti- *T. gondii* antibodies. From the Brazilian coastal and offshore waters, three out of five *T. chlororhynchos* (60%) showed anti- *T. gondii* antibodies (Suppl. 2). The highest occurrence was observed in *T. chlororhynchos* and *S. dactylatra* (60% and 45%, respectively), albeit lower sample sizes for these species. In the present study, all MAT-Toxoplasma titers scored two times above the cutoff (1:5), therefore resulting 10, at least, while one *S. dactylatra* and four *S. leucogaster* reached titers of 640, seven times above the cutoff.

The titration results did not present a normal distribution. Neither species (Kruskal-Wallis and Mann-Whitney U tests $p = 0.3$ and 0.08, respectively) nor colonies presented significant differences of antibodies titrations (Mann-Whitney U test $p = 0.14$).

This study investigated anti-*lLeptospira* antibodies in *S. dactylatra*, *S. leucogaster*, *P. aethereus*, *P. arminjoniana* and *T. chlororhynchos*. All sampled individuals were seronegative for the tested serovars, despite the presence of rats and mice on islands. Despite using an extensive bank with 19 serogroups containing 23 serovars from 5 different species in MAT-Leptospira (Suppl. 1) to increase sensitivity, we did not detect any seropositive animals. Birds have already been identified as renal carriers of *Leptospira* (Jobbins and Alexander 2015), and marine contacting animals have also been identified through serological tests (Colegrove et al. 2005; Silva et al. 2021) and molecular methods (Cameron et al. 2008). However, the result presented here agrees with previous reports that have analyzed the presence of anti-*Leptospira* antibodies in seabirds in Latin America (Vieira et al. 2018; Acosta et al. 2019; Silva et al. 2021). Conducting additional experiments in locations with a higher abundance and close vicinity to domestic and synanthropic animals, such as rats, would be important. Although consumption within colonies of invasive rodents by the seabird species studies is highly improbable, the contamination of soils and nest areas by these mammal invasive predators represents a noteworthy potential source of habitat contamination (Poulle et al. 2021). Orlando et al. (2020) conducted a study on anti-*Leptospira* antibodies in both wild and domestic animals residing in the same rescue center in Ecuador. They found high levels of these antibodies in wild animals, suggesting that they were infected with *Leptospira*. This also suggests that there may be a potential transmission route from domestic animals to wild animals.

Also, our study is the first to record *T. gondii* seropositivity in free-living *P. arminjoniana* and *T. chlororhynchos*, both seabird species breeding in remote Atlantic Ocean islands, Trindade and Tristan da Cunha and Gough, respectively, and remaining in high seas throughout the non-breeding period (Ramos et al. 2017; Carneiro et al. 2020). The MAT protocol used in the present study for detection of anti-*T. gondii* antibodies is the test of choice for wild animals and it has been previously used for seabirds (Deem et al. 2010; Dubey 2010; Dubey et al. 2016, 2021; Gennari et al. 2016a, b; Acosta et al. 2018, 2019). It presents good sensitivity and specificity and does not require species-specific conjugates. In the present study, the seroprevalence among the seabirds (34.5%; 111/322) was found to be slightly higher than the average occurrence (30.65%) previously found in studies with marine free-living birds from Brazil, in which results ranged from 12.4 to 79.7% (Gennari et al. 2016a, b; Acosta et al. 2018). This occurrence is similar to that reported by Gennari et al. (2016a) using the same serological test in a previous study that included three species—*P. aethereus, S. dactylatra* and *S. leucogaster* also from Abrolhos—and analyzing considerably lower number of samples ($n = 24/69$–34.8%). Another difference from the results presented here is that Gennari et al. (2016a) reported that all seabirds analyzed had lower MAT titers, 1:10 or 1:5, except for one *S. leucogaster* (MAT titer 1:640). Our results showed that most seroreactive seabirds had final titration between 1:10 and 1:80 and the result 1:40 was observed for all species. The encounter of frequent high titers suggests that the studied birds could be participating in the *T. gondii* life cycle as intermediate hosts, since the comparison with the cutoff values indicates probable acquired infection, as observed elsewhere (Dubey 2010).

Previous studies on islands without domestic cats found anti-*T. gondii* seropositive birds (Deem et al. 2010; Acosta et al. 2019). In Abrolhos, domestic cats were introduced to Santa Barbara Island at the end of 1997, having access to the sampled colonies, but were eradicated in 2005 (Campolina 2013). Currently, both Abrolhos and Trindade are considered free of cats (Campolina 2013; Leal et al. 2017), but recent evidence suggests an environmental contamination due to human-induced changes, that could decrease the habitat quality for marine birds, exposing them to industrial, mining and sewer residues (Nunes et al. 2022). Based on these studies, the diet of seabirds (Cherel and Klages 1997; Colabuono et al. 2006), and considering our results about *T. gondii* seroreactive seabirds, we suggest that there are chances of sporulated *T. gondii* oocysts being transported to the studied environment, as reported previously (Lindsay et al. 2003; Massie et al. 2010).

Oocysts of *T. gondii* from feline feces can contaminate marine waters through sewage and freshwater runoff (Dubey et al. 2021). In aquatic ecosystems, oocysts can accumulate in filter-feeding bivalves (Lindsay et al. 2004) and filter-feeding fish (Massie et al. 2010), that act as paratenic or transport hosts of *T. gondii*. Seabirds and mammals are intermediate hosts for this opportunistic parasite. Seabirds of this study feed on a variety of marine organisms, including fish, crustaceans, molluscs (cephalopods), and planktonic organisms, except for albatrosses, which may occasionally ingest other birds (Schubart et al. 1965; Cherel and Klages 1997; Colabuono et al. 2006).) Acute fatal toxoplasmosis in a red-footed booby (*Sula sula*) from Hawaii, USA, was previously reported (Work et al. 2002), whereas seabirds sampled during our study seem apparently healthy. Wild birds are either prone to acute disease and highly susceptible to *T. gondii*, as canaries (Dubey 2010), or demonstrate lower interactions with the parasite, like carrion-eating birds (e.g. vultures) that are resistant to *T. gondii* infection (Dubey et al. 2021). Interestingly, Zanet et al. (2023) demonstrate a high prevalence of *T. gondii* (37 out of 159 analyzed samples) in Italian “birds of prey”, indicating that the previously held assumption that these birds are "resistant to *T. gondii*" may require reevaluation. Considering the variation in susceptibility aspects among species, the results presented here suggests that more studies are necessary to follow, disclosing the role of species of seabirds as reservoirs of *T. gondii* in Brazil.

The presence of *T. gondii* antibodies in seabirds sampled indicates the potential parasite occurrence and circulation in their habitats, not only in coastal zones, but also in oceanic areas. It is worth to mention that the higher serologic titers were found in species that breed in coastal islands, with titers ranging between 10–640, while offshore adapted species (*P. arminjoniana* and *T. chlororhynchos*) presented lower titers, that ranged between 10 and 80. While sample size for *T. chlororhynchos* was small, the remaining species were well represented, according with the number of specimen allowed to capture under the government permission, and thus our results potentially indicate that coastal colonies may be at higher risks of infection, possibly due to environmental changes on natural resources, considering the regular human presence in these areas and even wider pollution from tailings dam failure in coastal areas (Nunes et al. 2022). Furthermore, the overdispersion and lack of significance shown in the GLMs highlights the need to use larger sample sizes to investigate the factors involved in increased risks. Also, we do suggest that future studies use tests with continuous responses for the titration (e.g. quantitative test), which can explore the variation between sample sites and species at a finer scale. However, the non-parametric tests did not reveal a statistically significant difference between species or colonies. This lack of significance may be attributed to the high number of non-seroreactive individuals, truncated titration results, and varying sample sizes among the groups. The p-values (between 0.8 and 1) on pairwise Mann-Whitney U tests are also potentially a result of the truncated and tied values on titration, reinforcing the need for finer scale tests. Experimentally infected pigeons (*Columba livia*) showed higher serological titers of IgG after ingestion of *T. gondii* oocysts (de Godoi et al. 2010) when compared to wild crested caracaras (*Caracara plancus*) that were fed tissue cysts with bradyzoites (Vitaliano et al. 2010) and in both experiments, antibodies started to become undetectable after 60 days post infection. Based on our observations of frequent occurrence of high titers, as a 4x-fold rise in antibody anti-*T. gondii* titers (i.e. equal or higher than 1:20) indicates probable acute acquired infection (Dubey 2010), it is likely that the birds in this study recently ingested oocysts. Despite their wide distribution and optimal movement capacity, we were unable to link the infection to any local conditions typically considered as potential risk factors. Therefore, it is plausible that the infection occurred elsewhere. Direct diagnostic of the parasite, whether through bioassays in mice or DNA detection from tissues of fallen birds would help enlighten the status of the chronic *T. gondii* infection in seabirds and their impact in the maintenance of the parasite cycle.

The infection by *T. gondii* in migratory birds, especially seabirds, have epidemiological significance given that parasites can be transported with the host and the introduction of *T. gondii* in a new geographic location can, potentially, be a threat to populations health and balance (Dubey et al. 2021). This kind of dispersion has already been described in Chile, where the Magellanic penguin (*Spheniscus magellanicus*), which migrate along the South American coastline, presented seropositive results (Acosta et al. 2018, 2019), demonstrating that further studies concerning the kinetics of parasite infection and the degree of susceptibility of seabirds are needed to better understand the role of avian hosts in the wildlife epidemiological cycle of *T. gondii*.

Seabirds, though strictly marine, rely on terrestrial environments for breeding e.g., coastal and oceanic islands, increasing their contact with pathogen reservoirs like invasive mammals. During breeding, they nest in dense colonies and explore foraging areas, leading to mixed-species aggregations at sea. This includes species from different colonies and long-distance migrants, potentially facilitating significant microorganism dispersal among conspecifics if contamination occurs (Schreiber and Burger 2001). In this context, the life history traits of seabirds reinforce their relevance in studies considering their role as hosts of *T. gondii*, a protozoan parasite that can infect various species of mammals and poses a zoonotic risk. The recognition of collaborative, interdisciplinary approaches demonstrate the interconnectedness of human health, animal health, and the environment. Finally, this study showed that although there was no serological indication of *Leptospira* infection in seabirds, at least 34.5% of the tested birds were seroreactive to *T. gondii,* some of them with high titers, suggesting acquired infection and a possible participation of seabirds in the *T. gondii* life cycle as intermediate hosts. Further studies of prevalence of anthropogenic related and emerging diseases in seabirds should be continuously carried out and incorporated into public policies, especially regarding long distance migrants as those present in our study.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11259-024-10575-x.

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Author contribution I.C.L.A.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing—original draft, Writing -review & editing. D.P.C.: Conceptualization, Data curation, Formal analysis, Validation, Visualization, Writing -review & editing. P.P.S.: Data curation, Investigation, Methodology, Visualization, Writing -review & editing. G.C.: Formal analysis, Validation, Visualization, Writing -review & editing. H.F.J.P: Resources, Validation, Visualization, Writing -review & editing. M.B.H.: Resources, Validation, Visualization, Writing -review & editing. A.F.S.F.: Formal analysis, Validation, Visualization, Writing -review & editing. C.C.: Data curation, Investigation, Methodology, Validation, Visualization, Writing -review & editing. C.A.M.: Project administration, Resources, Validation, Visualization, Writing -review & editing. T.S.N.: Project administration, Resources, Validation, Visualization Writing -review & editing. M.A.E.: Validation, Visualization, Writing -review & editing. G.T.N.: Investigation, Methodology, Project administration, Resources, Validation, Visualization, Visualization Writing -review & editing.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate This study adopted the Ethical Principles in Animal Research according to Brazilian College of Animal Experimentation and was approved by the Ethical Committee for Animal Research of the Faculty of Veterinary Medicine, University of São Paulo (Protocol No. 9959300821); Animal Use Ethical Committee at FURG (P040/2018) and Animal Use Ethical Committee at UFRGS (37905) with authorization of the Chico Mendes Institute for Biodiversity Conservation, Brazil (Sisbio No. 64381–2; 64234–9).

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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