Research Article

# Invasive house (*Rattus rattus*) and brown rats (*Rattus norvegicus*) threaten the viability of red-billed tropicbird (*Phaethon aethereus*) in Abrolhos National Park, Brazil.

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**Abstract**

Destruction of nests and predation by introduced species are among the main factors responsible for seabird declines.The red-billed tropicbird (*Phaethon aethereus*) is a tropical, colonially nesting seabird whose distribution in Brazil is restricted to a small, isolated breeding colony located within Abrolhos National Park. This represents the southernmost population of the species in the western Atlantic, and is among the most southerly in its global distribution. Despite its isolation, the population on Abrolhos is threatened by egg predation by two invasive rat species: the house rat (*Rattus rattus*) and brown rat (*Rattus norvegicus*). In this study we conduct a population viability analysis of *P. aethereus* in Abrolhos to estimate the potential long term impacts of the rats. Our results indicate that egg and chick predation by rats has the potential to quickly drive the Abrolhos tropicbird population into serious decline. Reducing this threat may require the urgent implementation of a rat control program.

**Keywords**: seabird, conservation, eradication, *Rattus*, population viability.

**Resumo**

O Rabo-de-palha-de-bico-vermelho (*Phaethon aethereus*) é uma ave marinha tropical e colonial. No Brasil, essa espécie apresenta distribuição restrita, com uma pequena e isolada colônia nidificando dentro do Parque Nacional Marinho dos Abrolhos. Essa população está localizada no limite sul da distribuição da espécie no Oceano Atlântico ocidental, e entre as populações mais ao sul de sua distribuição global. Apesar de seu isolamento, a população de Abrolhos está ameaçada pela predação de ovos e filhotes por duas espécies invasoras de rato: rato doméstico (*Rattus rattus*) e rato marrom (*Rattus norvegicus*). Neste estudo realizamos uma análise de viabilidade populacional de *P. aethereus* em Abrolhos para estimar os potenciais impactos de longo prazo causados por esses ratos. Nossos resultados mostram que a população foi considerada viável sob condições ambientais naturais. No entanto, a predação por ratos foi identificada como uma potencial ameaça capaz de rapidamente levar a população dessa ave a um acentuado declínio. Para que essa ameaça possa efetivamente ser contornada defendemos que a implementação de um programa de gestão direcionado para controlar a população de ratos em Abrolhos deve urgentemente ser colocada em prática.

**Palavras chaves**: aves marinhas, conservação, erradicação, *Rattus*, viabilidade populacional.

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## Introduction

The current crisis of global biodiversity loss and species extinctions requires the urgent implementation of long-term conservation actions [1]. Among birds, colonial breeding seabirds are most threatened [2, 3]. Indeed, out of the 346 species of seabirds in the world, 28% are listed as threatened and 10% as Near-Threatened [3]. Seabirds are threatened by a combination of interlinked factors, most notably competition with the fishing industry [4, 5], climate change [6], degradation of breeding sites, and egg/chick predation by introduced species [7].

On oceanic islands and archipelagos the most serious threat to colonial seabirds is often the introduction of non-native species [3]. Invasive rodents have probably had the largest impact on seabird populations and occur on over 90% of all islands worldwide [8]. Seabird breeding colonies are particularly vulnerable to rats because most species nest on the ground or in burrows, and chicks are poorly adapted to escape from predators [9]. Rats have been observed to prey on seabird eggs, chicks, and adults, and are estimated to be directly or indirectly responsible for 42% of bird extinctions on islands [10, 11].

Brazil's seabirds are of considerable conservation importance, representing 10.5% of species on the national red list and containing several species with >95% of their populations restricted to one or two breeding sites [12]. Among this latter group is the red-billed tropicbird (*Phaethon aethereus*), a tropical colonially-nesting seabird with restricted geographic range, high breeding site fidelity, great longevity, late sexual maturation, and annual reproduction [13, 14]. Some of these characteristics are associated with high extinction risk for seabirds [3, 15]. The most important breeding colony of the red-billed tropicbird in Brazil is located on the Abrolhos archipelago. This represents the southernmost population in the western Atlantic, and is one of the most southerly sub-populations in its entire distribution [14]. Such peripheral populations are predicted to be at the margins of viability in comparison to those occupying the core of the species range [16, 17]. Moreover, such populations are often morphologically, genetically, and/or ecologically distinct [17], making them targets for conservation [18].

A clear understanding of the necessary conditions for the long-term maintenance of seabird populations is important for the development of effective conservation strategies [19]. Such understanding can be gained through the use of population viability analyses (PVAs), a widely used tool in conservation to assess extinction risk and guide conservation actions [20-22]. In this study we use PVA to estimate the extinction probability and identify threats to the viability of the red-billed tropicbird population in the Abrolhos archipelago.

## Methods

### *Study area*

Data collection was carried out in the Abrolhos archipelago, a set of five oceanic islands located approximately 70 km off the central Brazilian coast (17°20-18°10'S, 38°35'-39°20'W) (Fig. 1). The archipelago is a Marine National Park, excluding the largest island, Santa Barbara, which is under the jurisdiction and control of the Brazilian Navy [23]. Abrolhos houses the largest breeding colony of red-billed tropicbird in Brazil [24], with breeding sites in all the islands of the archipelago. The native fauna of Abrolhos is composed of insects, arachnids, lizards and seabirds [25]. However, the archipelago has been subject to numerous introductions (both planned and unintentional) of non-native species. The current invasive fauna include cockroaches, goats, and two species of rats: the house rat (*Rattus rattus*) and the brown rat (*R. norvegicus*) [26].

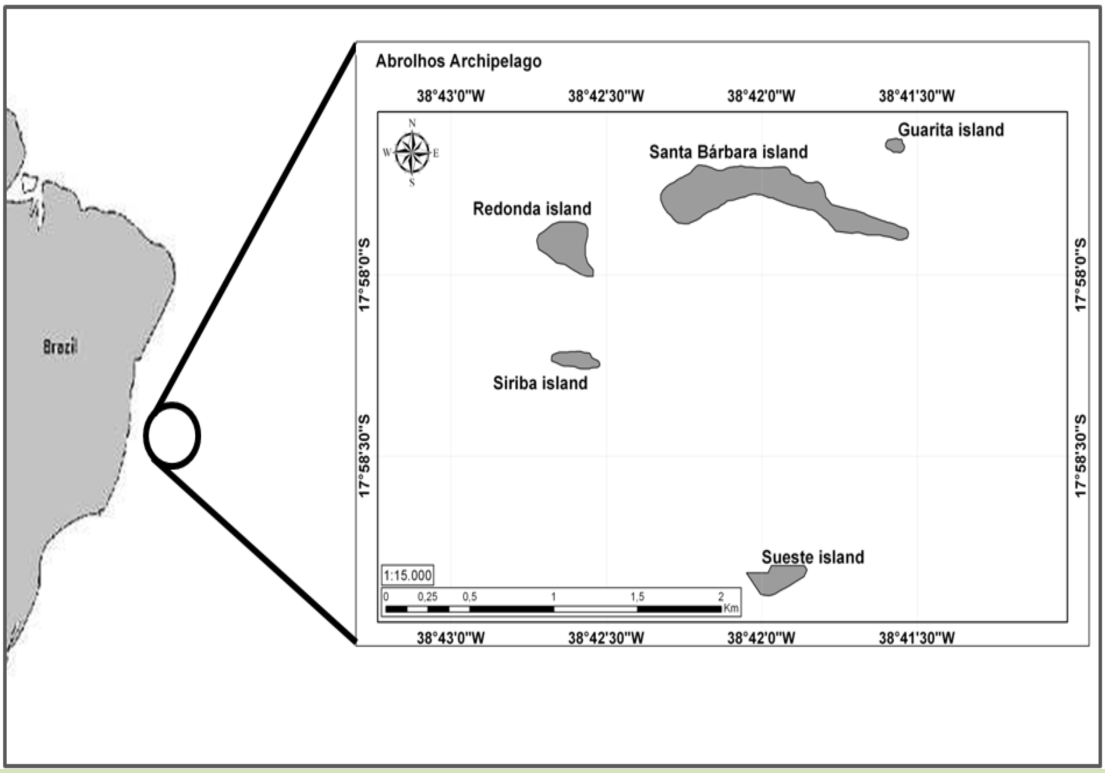


**Fig. 1. Map of the five islands that form part of the Abrolhos Archipelago, located approximately 70 km off the Brazilian coast, Atlantic Ocean.**

### *Data collection*

Demographic data were collected through a live capture-mark-recapture conducted over a nine year period, with sporadic expeditions from 1991 to 1998 and bimonthly expeditions in 2011 and 2012. In the 2011-2012 period the nests were labeled, geo-referenced and checked for the presence of adults, chicks, and eggs. These procedures took place as part of the Monitoring Program of Abrolhos Birds, coordinated by AVIDEPA (a Brazilian conservation Non-Governmental Organization). Red-billed tropicbirds lay one egg and raise one chick per year, nesting in holes, cliffs and rock crevices [27]. Nests where either the egg or the chick disappeared before the minimum incubation or chick's development period had been completed (42 and 84 days, respectively [28]) were considered predated. As the red-billed tropicbird has high site fidelity (returning to their natal island and nest site every year) [13], we could link individuals to a specific breeding site. The rare individuals that did not return to their original breeding site and bred on an alternative island were classified as dispersing animals. Based on nine years of observations, we made the assumption that rats are the only possible predator of these birds, since the other fauna are either too small (e.g. insects, arachnids, small lizards) or ecologically unsuited to predation (e.g. other seabirds and goats). There are no gulls in Abrolhos, and even though frigate birds (*Fregata magnificens*) are present, they are prevented from attacking eggs and chicks by the tropicbird's behavior of nesting in burrows or crevices. This strategy effectively protects eggs and chicks from larger seabirds, but makes them especially vulnerable to predation by rats.

### *Life history and population attributes*

The red-billed tropicbird is a tropical, long-lived, monogamous, colonially-nesting seabird, with late sexual maturation and annual reproduction [3, 13]. Its diet is based on fish captured in the open ocean, and breeding takes place on remote oceanic islands [29, 30]. In some populations reproduction occurs during restricted periods (usually during spring and summer), whereas other populations lay eggs all year round [13]. Eggs are incubated for 42 to 46 days and parents feed chicks with semi-digested food until they form plumage (70 to 91 days) [28]. Full adult plumage takes 2 to 3 years to develop, and individual birds may live from 16 to 30 years [31]. Red-billed tropicbirds are classified as threatened in Brazil [32].

### *Population Viability Analysis (PVA)*

The PVA was performed using the software VORTEX (Version 9.99b)[33]. VORTEX simulates survival and reproductive events in successive years for each individual in the population using the Monte Carlo method. It models the effects of deterministic and stochastic processes on the dynamics of the population [34]. A detailed description of the software and its features is given by Lacy [33, 34].

Population viability was modeled for 100 years [34]. The generation time of the red-billed tropicbird was estimated as 8.5 years, meaning that a 100-year simulation covers approximately 11 generations. We used 1,000 interactions [35] in each modeling scenario, and extinction was defined as the complete removal of at least one sex [36]. We adopted a metapopulation approach, which is more realistic for the Abrolhos archipelago because the species has high breeding site fidelity and we could therefore accurately estimate dispersal rates among islands of the Archipelago.

Since there is no strong evidence for food or other environmental limitations, we used maximum habitat availability (measured as the number of available nesting sites) as a measure of carrying capacity of each island. Tropicbirds are known to vigorously defend their burrows or nests, and the availability of burrows is often a limiting factor, sometimes causing extensive breeding failure [13].

In order to estimate survival rate and metapopulation size, we used Pollock's *robust design* model, which is a combination of the Cormack-Jolly-Seber (CJS) [37-39] live-recapture model and the closed capture models [40], using the software MARK [41]. In this model, instead of just one capture occasion between survival intervals, multiple capture occasions were used. This allowed the estimation of the temporary emigration from the trapping area and more precise estimates of survival because of the additional information on capture probabilities. For this analysis we used a seven-year data period; 1991 and 1998 were excluded from the analysis because we had just one visit per year, resulting in just one capture occasion (for more details see [42, 43]).

The initial population size and percentage of breeding females were calculated based on the size of the metapopulation (see carrying capacity above), the total number of nests recorded, and the number of active nests on each island. Dispersal rate was estimated as the number of individuals migrating from one island to another (individuals found nesting in different islands in different breeding periods). The genetic parameters are based on the VORTEX 9.99b default values of 3.14 lethal equivalents with 50% of that due to lethal alleles [33]. Population attributes and life history variables included: breeding system, maximum age of reproduction, age of the first successful breeding, maximum number of brood and progeny per year, and sex ratio. These parameters were estimated from field monitoring and supported, when necessary, by the published scientific literature [13, 28, 44, 45]. The summary of all parameters used as input data to the PVA is given in Table 1.

Table 1. Life history parameters of Red-billed Tropicbirds (*Phaethon aethereus*) used as input to computer program VORTEX for Population Viability Analysis of the population breeding at Abrolhos Archipelago in the southwestern Atlantic Ocean. ASB: Santa Barbara island, ASI: Siriba island, ARE: Redonda island and ASU: Sueste island.

| **Parameter** | **Base value of metapopulation** | **Source** |
|---|---|---|
| Breeding system | Monogamous | Orta (1992) |
| Maximum age of reproduction | 17 | This study |
| Age of first breeding | 4 | Schreiber & Burger (2001) |
| Maximum number of broods and progeny per year | 1 | Stonehouse (1962); Doherty *et al.* (2004) |
| Sex ratio (% males) | 50 | This study |
| % Adult female breeding | 79 | This study |
| % Males in breeding pools | 79 | This study |
| % Annual Mortality | 7 (14) | This study |
| Initial Metapopulation Size | 709 | This study |
| ASB | 387 | This study |
| ASI | 66 | This study |
| ARE | 172 | This study |
| ASU | 84 | This study |
| Carrying capacity (K) | 1095 | This study |
| ASB | 513 | This study |
| ASI | 95 | This study |
| ARE | 316 | This study |
| ASU | 171 | This study |
| Dispersal rate (%) | 1.50 | This study |
| Environmental variation, survival and reproduction | Concordant | |

*Predation scenarios*

We recorded the disappearance of eggs and chicks in the last two years of our monitoring program (2011 and 2012): in 2011, among 308 nests considered active, we registered and monitored a total of 103 eggs and 102 chicks in different stages, from which 73 eggs and 11 chicks were lost due to predation. In 2012, out of the 254 nests considered active, we recorded 81 eggs and 88 chicks, with a total of 42 eggs and five chicks lost to predation. Based on this data, we modeled three scenarios of nestling predation: high predation (79% of nestling mortality, as recorded in 2011), low predation (55% of nestling mortality, as recorded in 2012), and medium predation (67% nestling mortality, representing the mean of 2011 and 2012).

From a management perspective, it is important to project the outcome of potential conservation strategies to guide the implementation of on-the-ground rat eradication actions. We therefore created several hypothetical rat eradication scenarios, under the assumption that an effective decline in the rat population will result in a linear and proportional decline in nestling predation rate (e.g. an eradication scenario that culls 20% of the rat population will decrease nestling predation rates by 20%). We modeled the effects of hypothetical rat eradication programs on the probability of extinction of red-billed tropicbird population with eradication success ranging from 10% to 100% eradication (with scenarios of increasing eradication success in steps of 10%).

*Sensitivity analysis*

In order to examine the robustness of our models, we investigated model responses to uncertainty in estimated values of parameters used as input. We selected two population parameters: (1) percentage of females breeding, and (2) the effect of inbreeding depression. We modeled scenarios with a variation of - 20%, -10%, +10% and +20% for the percentage of reproductive females.The effect of inbreeding was examined by introducing inbreeding depression to the basic metapopulation scenario. The significance of the difference in output between the basic scenario and modified models was tested using a Student's t-test (two-tailed)[46].

## Results

Using the capture-recapture database, we estimated a metapopulation of 709 red-billed tropicbirds distributed among the four larger islands of Abrolhos archipelago, and a carrying capacity of 1,095 individuals based on the number of available nests. We estimated that 79% of the females were breeding, with an annual survival rate of 93% (7% mortality) (Table 1).

The metapopulation baseline model suggests that the red-billed tropicbird population at Abrolhos is likely to persist over the next 100 years, with a mean metapopulation size of 1,001 individuals retaining 99% of the original gene diversity (Table 2). Sensitivity analysis indicated that neither variation in the percentage of breeding females nor the inclusion of inbreeding depression has a strong influence on population trends (Table 2).

The medium (mean) and high nestling predation scenarios (67% and 79% mortality, respectively) were associated with an increase in the probability of extinction for the metapopulation from 0% (baseline scenario; current conditions) to 17% (mean predation scenario) and 98% (high predation scenario) (Fig. 2). Overall, this result indicates a very high sensitivity of the models to the predation parameter.

Table 2. Sensitivity analysis: variation of -10%, - 20%, +10% and +20% of the basic scenarios for % reproductive females and the effect of introducing inbreeding depression on the Population Viability Analysis for the Red-billed Tropicbird (*Phaethon aethereus*) at Abrolhos Archipelago in the southwestern Atlantic Ocean. *RSTOC*: Mean rate of stochastic population growth, P(E): Probability of extinction, GD: Genetic diversity of extant population.

| Scenarios | rstoc | Mean (SD) | P(E)100 (%) | Mean (SD) | Final Population Size | Mean (SD) | GD (%) |
|---|---|---|---|---|---|---|---|
| Basic scenario Metapopulation | 0.10 | 0.098 | 0 | 0 | 1001 | 105 | 99 |
| -10% female breeding | 0.09 | 0.098 | 0 | 0 | 882 | 123 | 98 |
| -20% female breeding | 0.07 | 0.097 | 0 | 0 | 846 | 139 | 98 |
| +10% female breeding | 0.12 | 0.097 | 0 | 0 | 922 | 104 | 98 |
| +20% female breeding | 0.13 | 0.098 | 0 | 0 | 929 | 92 | 98 |
| Inbreeding depression | 0.10 | 0.097 | 0 | 0 | 911 | 100 | 98 |

Significance of the difference in output between the basic and changed models was tested using a Student's two tailed *t*-test , *P<0.05.

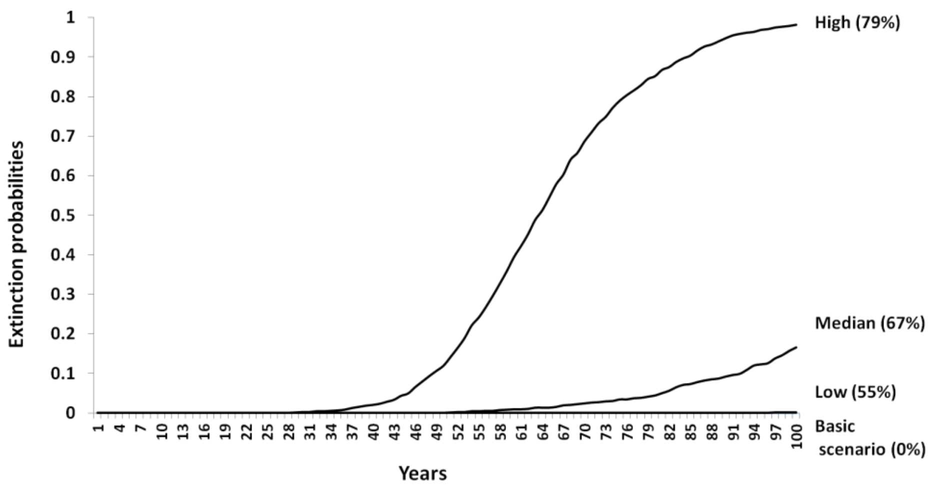


**Fig.2. Estimates of extinction probability due to predation on Red-billed Tropicbirds (*Phaethon Aethereus*) populations at Abrolhos Archipelago in the southwestern Atlantic Ocean. Three levels of predation were modeled: high predation (79% mortality, as recorded in 2011), low predation (55% mortality, as recorded in 2012) and a moderate predation value (67% mortality, as a mean from the above).**

In the rat eradication management scenarios, an increase in the control rate of the rat population was associated with a decrease in the probability of extinction. An eradication success of 40% (i.e., 40% of the rodent population removed) caused a dramatic reduction in the risk of population extinction (0.5% probability of extinction for the metapopulation) (Fig. 3).

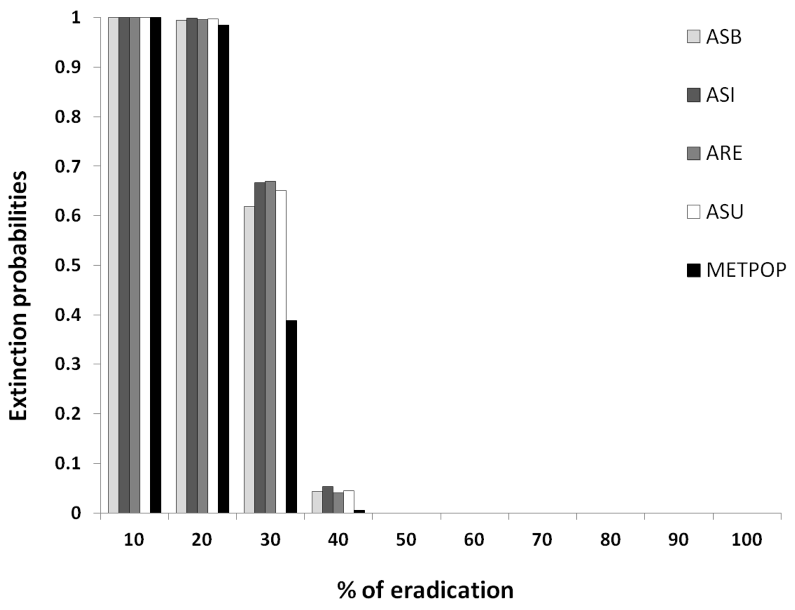


**Fig.3. Effect of rat eradication scenarios on probability of extinction of Red-billed Tropicbird (*Phaethon aethereus*) at Abrolhos archipelago in the southwestern Atlantic Ocean. The effect of eradication on the probability of extinction is given for the metapopulation, as well as in each of the subpopulations. ASB: Santa Barbara island, ASI: Siriba island, ARE: Redonda island, ASU: Sueste island and METPOP: Metapopulation.**

## Discussion

Besides the restricted global distribution of red-billed tropicbird, its total population size is small [47] and decreasing [14]. While populations at the core of the species' distribution exceed 1,000 pairs (Galapagos Islands and West Indians [47, 48]), Abrolhos hosts only a few hundred individuals [49]. The Abrolhos red-billed tropicbird population shows high levels of inbreeding and low levels of heterozygosity [50]. Nevertheless, there is no evidence of recent population bottlenecks in this population [50] and the estimated carrying capacity of 1,095 individuals and current population size of 709 individuals suggest that nest site availability is not currently limiting population growth.

Our baseline PVA (without rat predation) suggests that under historic ecological conditions, the population would remain relatively constant with a very low risk of extinction. However, when we factor in the impacts of the invasive rats, the prognosis changes dramatically with a high probability of extinction in the next 100 years under medium and high predation scenarios. Such a result is unsurprising: intense ecological impacts, such as predation, can significantly increase extinction risk by reducing the number of individuals, depressing reproduction rates, intensifying inbreeding effects, and accelerating the loss of genetic diversity [51-53].

Egg and nestling survival rates appear to be critical demographic parameters for population persistence of red-billed tropicbirds in Abrolhos. During the breeding period the tropicbirds establish colonies, confining a large portion of the population to a very small geographic area [54]. This is a physiologically stressful time for adults, during which eggs and nestlings are vulnerable to predation from ground-dwelling mammals [11, 55]. Red-billed tropicbirds are especially vulnerable to rats [56] because their nest sites (burrows and crevices, holes in cliffs and spaces between rocks)(Fig. 4a) are easily accessible by rodents, they have a long incubation period, and they lay only a single egg [13].

Invasive mammals have been responsible for the demise of insular bird species worldwide [57]. Rats were initially introduced to Abrolhos about 150 years ago when the first lighthouse was built and vessels began to regularly arrive at the archipelago [23]. In 1994, domestic cats were also introduced in a failed attempt to control the rat population. Indeed, cat removal eventually became necessary because they were threatening the resident breeding population of masked boobies (*Sula dactylatra*). After removal of the cats, the rat population began to increase again, to the detriment of the seabird colonies [cf. 58]. The two rat species found in Abrolhos are among the most ecologically damaging invasive species, with high impacts on seabird populations [8, 59, 60]. For example, a recent meta-analysis of rat-seabird interactions [11] documented 115 negative interactions on 61 oceanic islands, affecting 75 different species.

## Implications for conservation

Our results suggest that the future of the red-billed tropicbird population at Abrolhos National Park is highly uncertain due to the high rates of rat predation on eggs and nestlings. The population faces a high risk of decline, with a mean probability of extinction of 57.5% and mean time to extinction of only 75 years. In this context we have two different management options against alien mammals: control and eradication. Of these, eradication is the preferable and most effective management option from an ecological standpoint [60]. At least 1,224 successful eradications of invasive species have now been completed on 808 islands around the world [61] and there is good evidence that seabird populations can rapidly recover after the rodents have been removed [62].

Nevertheless, complete eradification may be difficult and costly, and long term sustainability requires stringent quarantine regulations to prevent future reinvasions [63]. Eradication would also require considerable political will and a relatively high level of financial investment. Given these difficulties, rat control may be a more feasible short-term option.Our results indicate that a decrease of 40% in the rat population would have a very positive impact on the viability of red-billed tropicbird population. Ultimately, the decision to eradicate or control rats on the archipelago should be based on a realistic cost-benefit analysis. Studies on other islands have typically indicated that although complete eradication is costly and time-consuming [e.g. 64], the cost-benefit ratio is ultimately superior to a rat control strategy [64].

The Abrolhos archipelago has various characteristics that favour the implementation of a rat eradication strategy: i) it has a very small resident human population (2 or 3 families restricted to Santa Barbara Island) limiting the inconvenience and reducing the probability of re-invasion of rats after eradification; ii) tourism is concentrated in the ocean zone of the park, with tourists being allowed entry to only one of the islands and always accompanied by a guide; iii) the archipelago is composed of five small islands (totaling around 0.45 km$^2$) (Fig. 4b) which are easier targets for eradication methods, and; iv) the close proximity to a major airport (162 km) significantly reduces costs [61], which increase with island isolation [65]. One possible complication is that the archipelago is politically divided under two national agencies: the Ministry of the Environment (responsible for managing the Abrolhos National Park) and the Ministry of the Defense (the Navy manages Santa Barbara, the largest island of the archipelago) (Fig. 4c). To be successful, the control/eradication programme would need to be conducted jointly by both sectors of the Brazilian government.

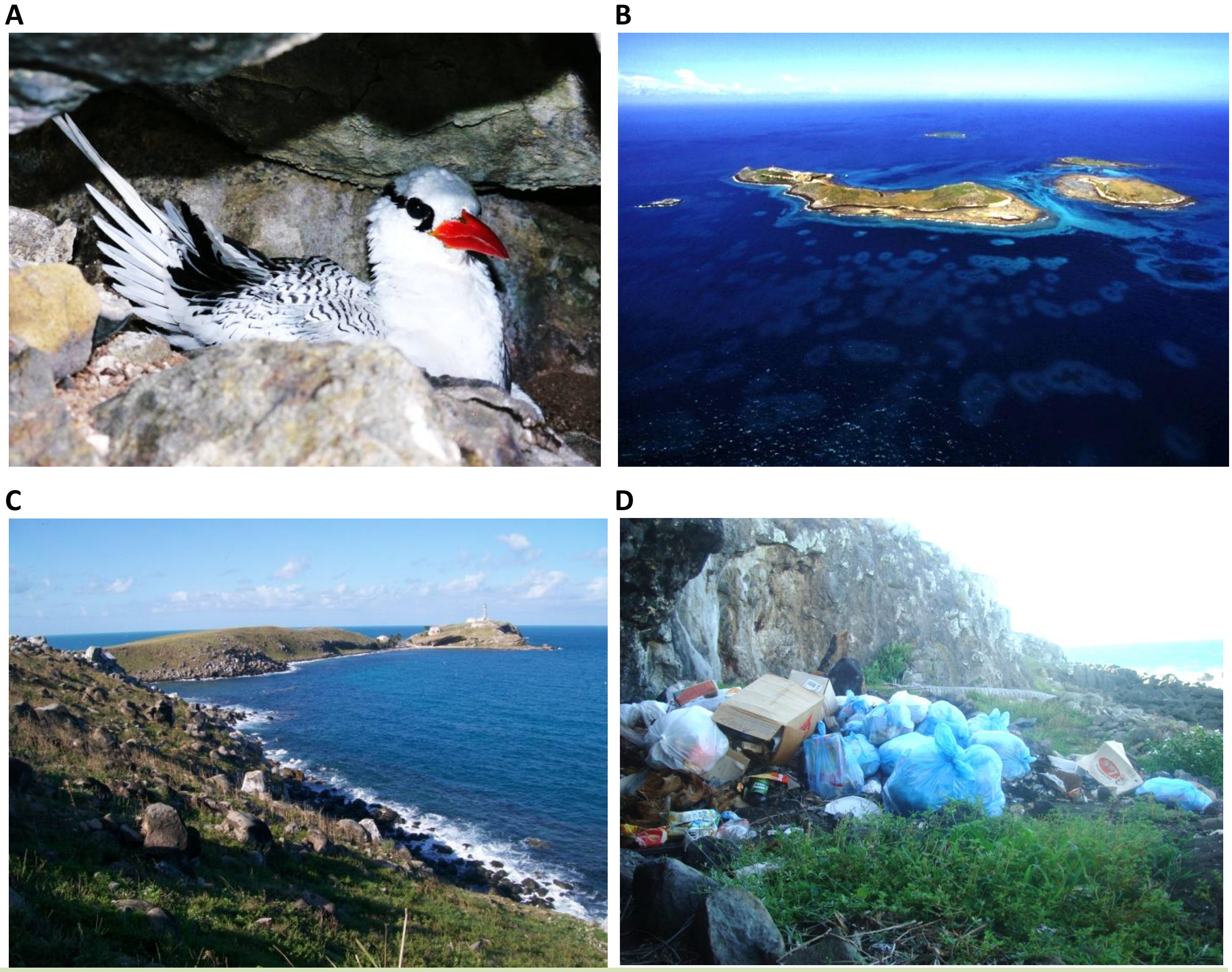


**Fig. 4. A) Nest site of a Red-billed Tropicbird (*Phaethon aethereus*) at Abrolhos archipelago. Photo credits: Cesar Musso, B) Complete view of the five small islands of the Abrolhos archipelago. Photo credits: Marcello Lourenço, C) View of the largest island of the archipelago. Photo credits: Gustavo da Rosa Leal and D) Accumulated waste produced by the resident human population. Photo credits: Raissa Sarmento.**

For these reasons,we strongly recommend the development and implementation of a management program to completely eradicate rats from Abrolhos National Park. Although such a program should be implemented as quickly as possible, it will be necessary to perform further research to identify optimal strategies for eradificaton. For example, analysis of palatability of different baits and studies on the feeding habits of the rats (e.g., stable isotope analysis of stomach contents) to identify periods of food scarcity. Additionally, effective conservation actions will need to include limiting alternative food sources for rats (e.g. garbage generated by the human population inhabiting the islands and also by tourism) and better sewage treatment. Currently all waste produced by the resident human population is allowed to accumulate on the island where it is eventually burnt - sometimes as infrequently as once a month (Fig. 4d). Ideally, waste should be quickly removed and collection/disposal intervals should be shortened. Moreover, strategies to properly contain and isolate waste material from rats in the period between flights should be put into practice.

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