

Impact of invasive species on the density and body size of an insular endemic lizard (*Trachylepis atlantica*)

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Abstract

Background Invasive species have been responsible for the extinction of several species around the world. The Noronha skink is an endemic lizard from the Fernando de Noronha archipelago, Brazil, that has been suffering from habitat changes and the introduction of invasive species.

Results The density of *Trachylepis atlantica* on the main island was 0.167 ± 0.090 individuals/m²; that on the secondary islands was 0.357 ± 0.170 individuals/m²; and that on the entire archipelago was 0.184 ± 0.109 individuals/m². Moreover, the morphometric parameters of the Noronha skink were compared between the main island and secondary islands. The values of all parameters were higher on the secondary islands.

Conclusion The occurrence of invasive species on the main island seems to be a determining factor in the density and body size of the Noronha skink.

Background

Due to their geographic isolation, oceanic islands show unique colonization dynamics, with elevated endemism and low species richness, which increase the population density of species in these environments [1,2,3]. However, oceanic islands have been losing their fauna, including their endemic species, since the fifteenth century due to human colonization [4,5].

Anthropic activities such as urbanization, pollution, habitat fragmentation, and introduction of invasive species are proven threats to the environment and biodiversity globally [6,7]. These threats are also responsible for the extinction and decline of species on the Fernando de Noronha archipelago [8], an oceanic archipelago located northeast of Brazil; the affected species include the extinct Noronha rat (*Noronhomys vespucii*) [9] and the Noronha skink (*Trachylepis atlantica*) [10].

The Noronha skink (Figure 1) is one of the oldest residents of the Fernando de Noronha archipelago, since radiation from its African ancestors occurred during the Miocene (10-27 million years ago) [11]. This is the lizard species located farthest east from South America [12] and is the only species of the genus *Trachylepis* in the New World.

Figure 1. Noronha skink (*Trachylepis atlantica*) (photography by Vinicius Gasparotto).

This lizard is charismatic and fearless towards humans due to its evolution and speciation in a predator-free environment and shows important ecological functions associated with the equilibrium of the archipelago ecosystem. One of these functions is the pollination of plants such as mulungu (*Erythrina velutina*) when the skink visits its flowers searching for nectar [13].

Although a reduction in the abundance of *T. atlantica* can be easily visualized on the archipelago, it is now also being reported by local inhabitants. Considering that the skink is endemic to Fernando de Noronha in an area smaller than 30 km², in 2017, this species was designated as threatened by the State of Pernambuco, which administers the archipelago [10].

The present work aimed to determine the density and morphometry of this species and to associate these findings with the human presence, anthropic activities and threats caused by invasive species. As of the time of writing, this study was the first to examine the density and perform morphometric comparisons of *T. atlantica* between the islands of the archipelago.

Results

Density and abundance

A total of 488 individuals were counted at 150 point transects (Figure 2), including 113 (75.3%) on the main island, 19 (12.6%) on Rata Island, 16 (10.7%) on Meio Island, 1 (0.7%) on Chapeu Island, and 1 (0.7%) on Morro da Viuvinha Island. The counts varied from 0 to 19 individuals and the density in the sampling areas from 0 to 1.51 individuals/m². In 36 (24%) of the transects, no skinks were observed. Of the 150 point transects, 65 (43.3%) were located in forest, 15 (10%) in grassland, 23 (15.3%) in rocky coast/quarry, 22 (14.7%) in shrub, and 25 (16.7%) in urban landscape.

Figure 2. Point transects performed from 2015 to 2018 to determine *Trachylepis atlantica* density and distribution in Fernando de Noronha archipelago.

atlantica density was estimated to be 0.167 ± 0.090 individuals/m² on the main island, 0.357 ± 0.170 individuals/m² on the secondary islands (Rata, Meio, Chapeu, and Morro da Viuvinha), and 0.184 ± 0.109 individuals/m² across the entire archipelago of Fernando de Noronha. No covariate was used to obtain the detection functions, since no covariate model could be fitted. The resulting density and distribution map is shown in Figure 3.

Figure 3. Density and distribution of the Noronha skink (*Trachylepis atlantica*) in Fernando de Noronha archipelago.

The abundance of *T. atlantica* was estimated to be 3,295,440 individuals in the archipelago of Fernando de Noronha, including 2,820,630 (85.6%) individuals on the main island and 474,810 (14.4%)

individuals on the secondary islands. The total area of the archipelago is 18.22 km², the main island 16.89 km² (92.7%), and secondary islands, 1.33 km² (7.3%).

Morphometric evaluation

Among the 135 individuals captured between 2014 and 2016, 114 (84.4%) were from the main island, and 21 (15.5%) were from the secondary islands (10 from Rata Island, 7 from Meio Island, 2 from Sao Jose Island, and 2 from Chapeu Island). All morphometric parameters showed greater values on the secondary islands. Males from the secondary islands were larger and heavier than males from the main island (Table 2). Moreover, males were heavier and larger than females on both the main island and the secondary islands (Table 3).

Table 2. Mean values and differences in morphometric parameters of males and females of *Trachylepis atlantica* among the species captured on the main island and secondary islands of the Fernando de Noronha archipelago.

Parameter	Sex	Island	Mean	Mean difference (CI 95%)	p
Head length (CCab) (cm)	Female ^b	Main	1.44	-0.07	0.671
		Secondary	1.51	(-0.40; 0.26)	
	Male ^a	Main	1.76	-0.30	< 0.001
		Secondary	2.06	(-0.46; -0.14)	
Rostrum-cloaca length (CRC) (cm)	Female ^b	Main	7.93	-0.58	0.469
		Secondary	8.51	(-2.18; 1.02)	
	Male ^a	Main	9.40	-0.70	0.032
		Secondary	10.10	(-1.34; -0.06)	
Tail length (CCau) (cm) ^c	Female ^b	Main	11.88	-0.53	0.743
		Secondary	12.42	(-3.80; 2.73)	
	Male ^b	Main	14.27	-1.52	0.115
		Secondary	15.79	(-3.43; 0.38)	
Total length (CTot) (cm) ^c	Female ^b	Main	19.69	-1.24	0.058
		Secondary	20.93	(-6.19; 3.71)	
	Male ^a	Main	23.42	-2.29	0.036
		Secondary	25.71	(-4.43; -0.15)	
Weight (g) ^c	Female ^b	Main	12.46	-1.21	0.370
		Secondary	13.67	(-3.89; 1.49)	
	Male ^a	Main	18.21	-7.34	0.002
		Secondary	25.56	(-11.79; -2.90)	

Table 3. Mean values and differences in morphometric parameters between males and females of *Trachylepis atlantica* captured on the main island and secondary islands of the Fernando de Noronha archipelago.

Parameter	Island	Sex	Mean	Mean difference (CI 95%)	p
Head length (CCab) (cm) ^a	Main	Female	1.53	-0.23	< 0.001
		Male	1.76	(-0.34; -0.12)	
	Secondary	Female	1.68	-0.55	< 0.001
		Male	1.87	(-0.71; -0.38)	
Rostrum-cloaca (CRC) (cm) ^a	Main	Female	8.40	-1.02	< 0.001
		Male	9.42	(-1.43; -0.61)	
	Secondary	Female	9.06	-1.59	0.001
		Male	9.54	(-2.42; -0.75)	
Tail length (CCau) (cm) ^{a,c}	Main	Female	12.40	-1.81	< 0.001
		Male	14.21	(-2.76; -0.87)	
	Secondary	Female	13.58	-3.37	0.001
		Male	14.44	(-5.12; -1.61)	
Total length (CTot) (cm) ^{a,c}	Main	Female	20.80	-2.61	< 0.001
		Male	23.41	(-3.84; -1.38)	
	Secondary	Female	22.50	-4.95	< 0.001
		Male	23.99	(-7.00; -2.90)	
Weight (g) ^{a,c}	Main	Female	12.45	-6.62	< 0.001
		Male	19.08	(-8.94; -4.31)	
	Secondary	Female	16.60	-12.57	< 0.001
		Male	21.11	(-16.83; -8.32)	

Discussion

The present study estimated the population density of *T. atlantica* in different landscapes of the archipelago of Fernando de Noronha, providing information that was previously nonexistent. Comparison of the results of the present study with similar studies of the genus *Trachylepis* on other islands demonstrated that the density of *T. atlantica* is greater than that of *T. adamastor* (0.012 individuals/m²),

endemic to Tinhosa Grande Island [14], and *T. seychellensis* (0.021 individuals/m²), endemic to the Seychelles Islands [15].

The increased density of *T. atlantica* in comparison with those of other *Trachylepis* species may be explained by the fact that Tinhosa Grande Island has a small size and no vegetation, offering few resources for *T. adamastor*. In contrast, the Seychelles Islands have a larger area than Fernando de Noronha but harbors numerous natural and invasive predators of *T. seychellensis*, such as snakes and birds of prey [16]. Both the Tinhosa Grande and Seychelles Islands exhibit unfavorable environments preventing their *Trachylepis* species from reaching the densities observed for *T. atlantica*.

The phenomenon known as density compensation [17] explains the expected abundance of *T. atlantica* and why it is currently lower than expected. According to Buckley and Jetz [18], insular species tend to reach population densities above those of their continental conspecifics. An example of this phenomenon is provided by the tegu lizard (*Salvator merianae*), which presents densities of 6.9×10^{-4} individuals/m² in the main island of Fernando de Noronha [19] and 6.3×10^{-5} individuals/m² in continental Brazil (Espírito Santo State) [20], i.e., at least 10 times higher in insular environment.

The low native species richness of the Fernando de Noronha archipelago and the absence of natural predators prior to human occupation in the sixteenth century are probably the key factors in the high expected density of *T. atlantica* on the archipelago [21]. The lack of species sharing the same ecological niche as *T. atlantica* resulted in low interspecific competition, which, allied with the absence of natural predators, resulted in low predation rates during the early establishment of this species on the archipelago [21].

However, the current population density of *T. atlantica* may not be sufficient to maintain the species in the long term. If all the archipelago presented the same density found on the secondary islands, which are free of cats and exhibit low densities of tegu lizards [19], the abundance of the Noronha skink would be 6,504,540 individuals. Thus, it can be inferred that the actual population of *T. atlantica* is at least 50.7% below the expected abundance.

Due to the evolution and speciation of the Noronha skink in the absence of natural predators, behavioural defenses were also absent in this species, making it vulnerable in interspecific encounters with exotic predators. Currently cats, rats and cattle egrets are the main threats and prey upon *T. atlantica* individuals daily. Dias et al. [22] described the predation frequency of *T. atlantica* by cats reported by the resident inhabitants who maintain cats in their households with the aim of controlling the Noronha skink population.

The predation pressure generated by invasive species, especially cats, may directly influence the population densities of the *T. atlantica* recorded in the present study, especially in the urbanized region of the main island of Fernando de Noronha archipelago. This hypothesis is corroborated by Case and Bolger [23], who noted that cats are considered successful predators of small reptiles in several types of

environments. Smith et al. [24] concluded that the predation of reptiles by invasive species on Christmas Island was the main factor of the decline of its native reptiles.

Through stable isotope analyses and analyses of prey fragments in faecal samples of cats and rats and the stomach contents of tegu lizards, Gaiotto [25] determined the potential trophic relations of producers and consumers on Fernando de Noronha. The results showed that *T. atlantica* corresponded to 18.8% of the cats' diet and 30.3% of the rats' diet [25].

With the arrival of new invasive species in recent decades, such as the tegu lizard (*Salvator merianae*) and the cattle egret (*Bubulcus ibis*), the increase in the mortality rates and population decline of *T. atlantica* are concerning. According to Gaiotto [25], 19.6% of the tegu's diet is composed of *T. atlantica*. Silva-Jr et al. [26] also reported predation of cattle egrets upon *T. atlantica*.

The absence of a single invasive species with a high predation potential, such as cats, may have allowed the higher density of *T. atlantica* on the secondary islands (0.357 individuals/m²), which was 119% higher than the density observed on the main island (0.167 individuals/m²). Not only is the density higher, but the body size and mass of *T. atlantica* individuals are also significantly higher on the secondary islands than on the main island, despite the expected body size and mass of males being greater than those of females.

The greater body size and mass of *T. atlantica* on the secondary islands may also be related to longevity. Classic studies have shown that reptiles grow constantly during their lives and, according to Goss [27], amphibians and reptiles retain their cartilage epiphyses throughout their lives, allowing constant growth. These findings were corroborated by Andrews [28], who noted that even if growth is insignificant after reaching asymptotic size, reptiles grow throughout their lives.

According to Olsson and Shine [29], the constant growth of reptiles is best observed in some lizards with short longevity. This information corroborates the results of the present work. The secondary islands of the Fernando de Noronha archipelago have been subject to fewer anthropic interferences and harbor fewer invasive species, which may increase the longevity of *T. atlantica* compared to the individuals on the main island.

The effects of the insular conditions on body size are referred to as the "island rule" and may be associated with intrinsic (p.e., climate) or extrinsic (p.e., predation) factors [30, 31, 32]. According to Russell et al. [33], when islands exhibit the same biogeographic climatic conditions, extrinsic factors may not explain body size differences. However, the high predation rate of cats on the Noronha skink and competition with other invasive species have probably created selective pressure that determines the observed density and body size differences, resulting in population decline on the main island.

Conclusions

The morphometric comparisons showed that the longevity of *T. atlantica* on the main island is reduced compared to that of individuals on the secondary islands. The difference in the invasive species communities of the main and secondary islands is the most likely factor determining the density and morphometric parameter differences of *T. atlantica*. The results are robust to indicate the threats that this endemic species, *T. atlantica*, is subjected to, and these findings may contribute to mitigation actions and the inclusion of this species in the red list of IUCN.

Methods

Study area

The archipelago of Fernando de Noronha (3°51'13.71"S, 32°25'25.63"W) is composed of 21 islands and islets with a total area of 18.22 km² [22,34]. It is one of the four Brazilian oceanic insular sets, including the Archipelago of Sao Pedro and Sao Paulo, the Rocas Atol, Trindade and Martin Vaz Islands and the Archipelago of Fernando de Noronha.

The archipelago has a wet and dry tropical climate, with the rainy season occurring from March to July and the dry season from August to February [35]. Currently, the predominant vegetation of the archipelago is deciduous seasonal forest, similar to that in the Brazilian northeast [36]. On the south face of the archipelago, which is exposed to equatorial trade winds, the vegetation is arboreal with some patches where grass prevails [37]. The urbanized area is located in the center of main island, outside the Marine National Park (Figure 2).

Fernando de Noronha was discovered in 1503 by Vespucci and was occupied by several different countries, such as the Netherlands, France, Portugal and the United States; in 1942, it became Brazilian federal territory, and in 1988, it started to be administered by the Brazilian State of Pernambuco [36,38]. Currently, only the main island is occupied by humans, and the entire terrestrial area is occupied by two federal protected areas: a Marine National Park, which is an IUCN category II protected area covering 70% of the terrestrial territory, and a Protected Area designated as IUCN category V that is destined for human use, covering 30% of the terrestrial area. The estimated human population was 2.9 thousand inhabitants in 2017, with approximately 7.5 thousand concurrent tourists visiting the archipelago at a given time in 2016 [39].

The archipelago exhibits rich diversity of exotic and invasive species such as rats (*Rattus rattus* and *R. norvegicus*), mice (*Mus musculus*), rock cavies (*Kerodon rupestris*), domestic dogs (*Canis lupus familiaris*), domestic cats (*Felis silvestris catus*), cattle egrets (*Bubulcus ibis*), tegu lizards (*Salvator merianae*), and rococo toads (*Bufus jimi*) [34], especially in the main island. From this list, cats, cattle egrets, synanthropic rodents and tegu lizards were reported as predators of the *T. atlantica* [19, 22, 26, 40].

Cats were probably introduced to the archipelago with the first landing of the European colonizers, during the sixteenth century [22]. Considered as superpredators in insular environments and

responsible for the extinction of birds, mammals and reptiles on several islands worldwide [41,42], the cat population on Fernando de Noronha, is estimated at approximately 1,300 individuals, which is considered one of the highest densities on islands worldwide [22]. The cats are reported to occur only in the main island of the archipelago, at higher densities in the urbanized area of the Protected Area [22].

The synanthropic rodents are present in all islands of the archipelago at high densities [40]. The tegu lizards were introduced before 1918 [43] and the cattle egrets arrived naturally in the 1990's [43]. Although present in all islands of the archipelago, the tegu lizards and the cattle egrets are observed at higher densities in the urbanized area of the Protected Area and at lower densities or absence on the secondary islands [19, 44].

Study design

Five field campaigns were performed for 20 days each in February and November 2015, February, October and November 2016, and April 2018 to determine the density, distribution, and morphometry of the Noronha skink in different landscapes of the archipelago. This approach assumed no fluctuation of its density and distribution throughout the year.

To determine the density and distribution of the *T. atlantica* in the archipelago, point transects were chosen in accessible areas of the main island and some secondary islands, generating point abundance values. The points were located not only along trails or in human-altered habitats, but also in conserved landscapes inside the Marine National Park as well. This method was performed in all campaigns but at different sampling sites.

The morphometry parameters were obtained from opportunistic captures of *T. atlantica* during the field campaigns, but at different sites than the point transects, distributed both in the main island and secondary islands of the archipelago.

The study was approved by the Ethics Committee of the School of Veterinary Medicine of the University of Sao Paulo (CEUA protocol number 1827250515) and by the Brazilian Ministry of Environment (SISBio permit number 41682).

Point transects

The point transects were obtained on the main island and some secondary islands (Rata, Meio, Morro da Viúva, and Chapéu) of the archipelago. At each point transect, a single observer remained still for seven minutes, observing a 2 m radius area covering 12.6 m². The number of visualized individuals during the observation period was recorded and the observations were performed in all landscape types (forest, shrub, grassland, rocky coast/quarry, and urban), which were sampled during the day when the

temperature was approximately $29.8 \pm 2.2^{\circ}\text{C}$, during the period of increased activity for the species defined by Rocha et al. [12]. These inclusion criteria are essential for the observation of ectothermic animals, which are more active in warm periods of the day.

A database of the point transects which included the *T. atlantica* cluster size, bin start and end (0-2 m), landscape type (which was used as covariate in the abundance model), and effort (which was the same for all transects, since they were only visited once) was used to generate a detection function and the density/abundance estimations. To achieve that, the *Distance* package of R was used, considering that the recorded individuals in each point transect were clustered (for example, a colony) and a surveyed radius truncated at 2 m (i.e., we considered binned or grouped distance data), since the distances from the observer and the individuals could not be measured due to the fact that the skinks were elusive. Moreover, the best model (half-normal, hazard-risk and uniform) to fit the detection function was chosen according to its Akaike Information Criterion (AIC). The abundance of *T. atlantica* both in the main island and the secondary island was calculated using this model.

The distribution map was obtained using the *DSsim* package of R, using the mean density of the *T. atlantica* (previously obtained) as constant, adjusted by hotspots and lowspots given by the density observed in each point transect. These adjustments were based on the density of *T. atlantica* in each transect (recorded individuals divided by 12.6 m^2). The point transects were represented in a map.

Morphometric evaluation

To perform morphometric evaluation of *T. atlantica*, individuals were opportunistically captured on the main and secondary (Rata, Meio, Sao Jose, and Chapeu) islands at distinct points from those used under the density and distribution assessment methods. The individuals were obtained throughout the study period, from different landscape types of the archipelago.

The evaluated parameters were head length (HL), rostrum-cloacal length (RCL), tail length (TL), and total length (TotalL) measured with a rigid ruler (in centimetres) and body mass (in grams) measured with a digital scale with a one-gram precision. Autotomized animals and those with regenerating tails were not considered in the TL, TotalL or body mass analyses.

The morphometric parameters of the individuals were compared between the main and secondary islands and by sex. For this purpose, independent t-tests were used to compare the mean parameters. The variances of the parameters were checked by the Levene test.

Declarations

Ethics approval and consent to participate

Noronha skink sampling was approved by the Brazilian Ministry of Environment (SISBio permit number 41682) and the Ethics Committee of School of Veterinary Medicine of the University of Sao Paulo (CEUA protocol number 1827250515).

Consent for publication

Not applicable.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All authors collected data, RAD and TM performed statistical analysis, all authors wrote the manuscript. RAD led the project. All authors read and approved the final manuscript.

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Figures



Figure 1

Noronha skink (*Trachylepis atlantica*) (photography by Vinicius Gasparotto).

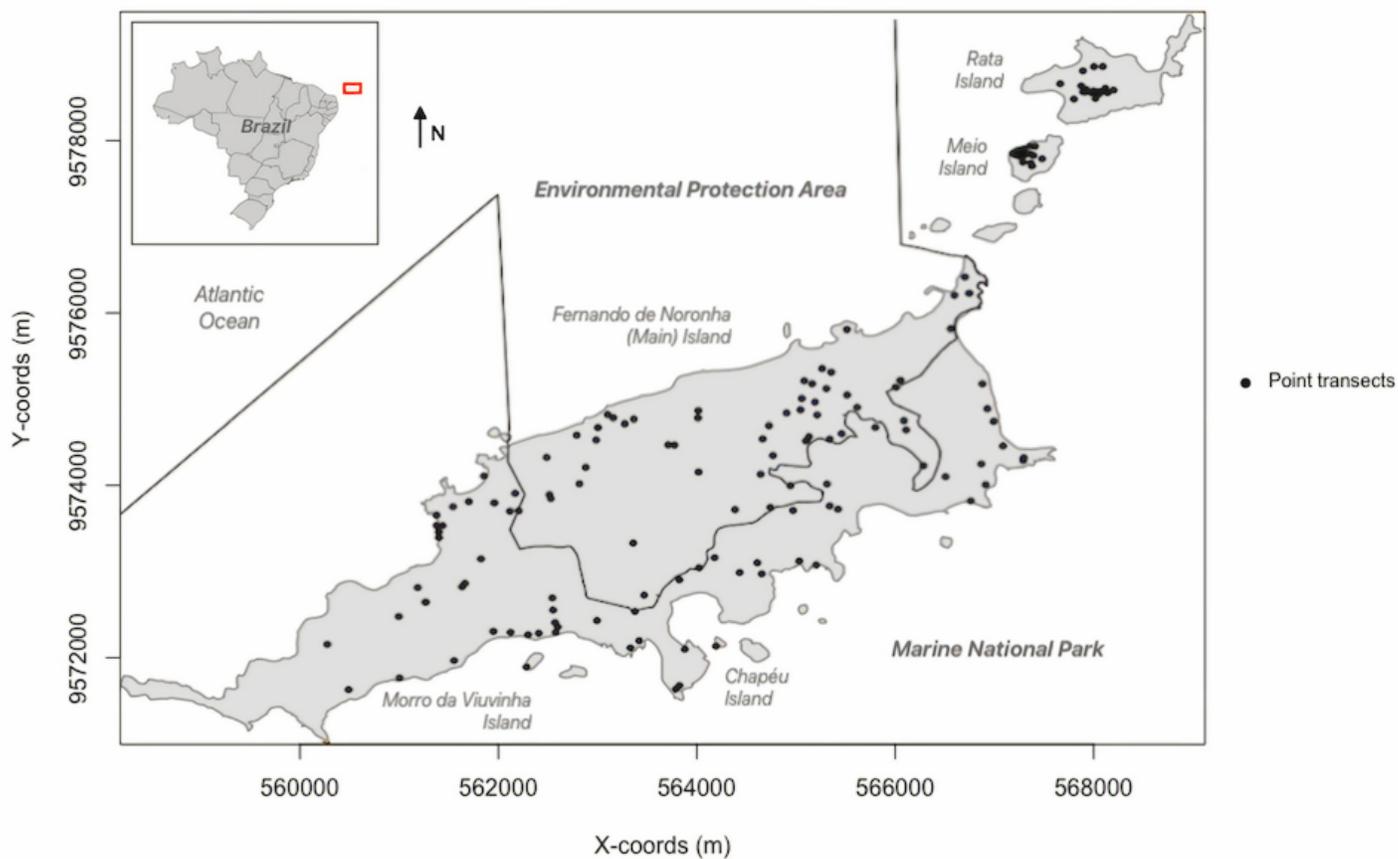


Figure 2

Point transects performed from 2015 to 2018 to determine *Trachylepis atlantica* density and distribution in Fernando de Noronha archipelago.

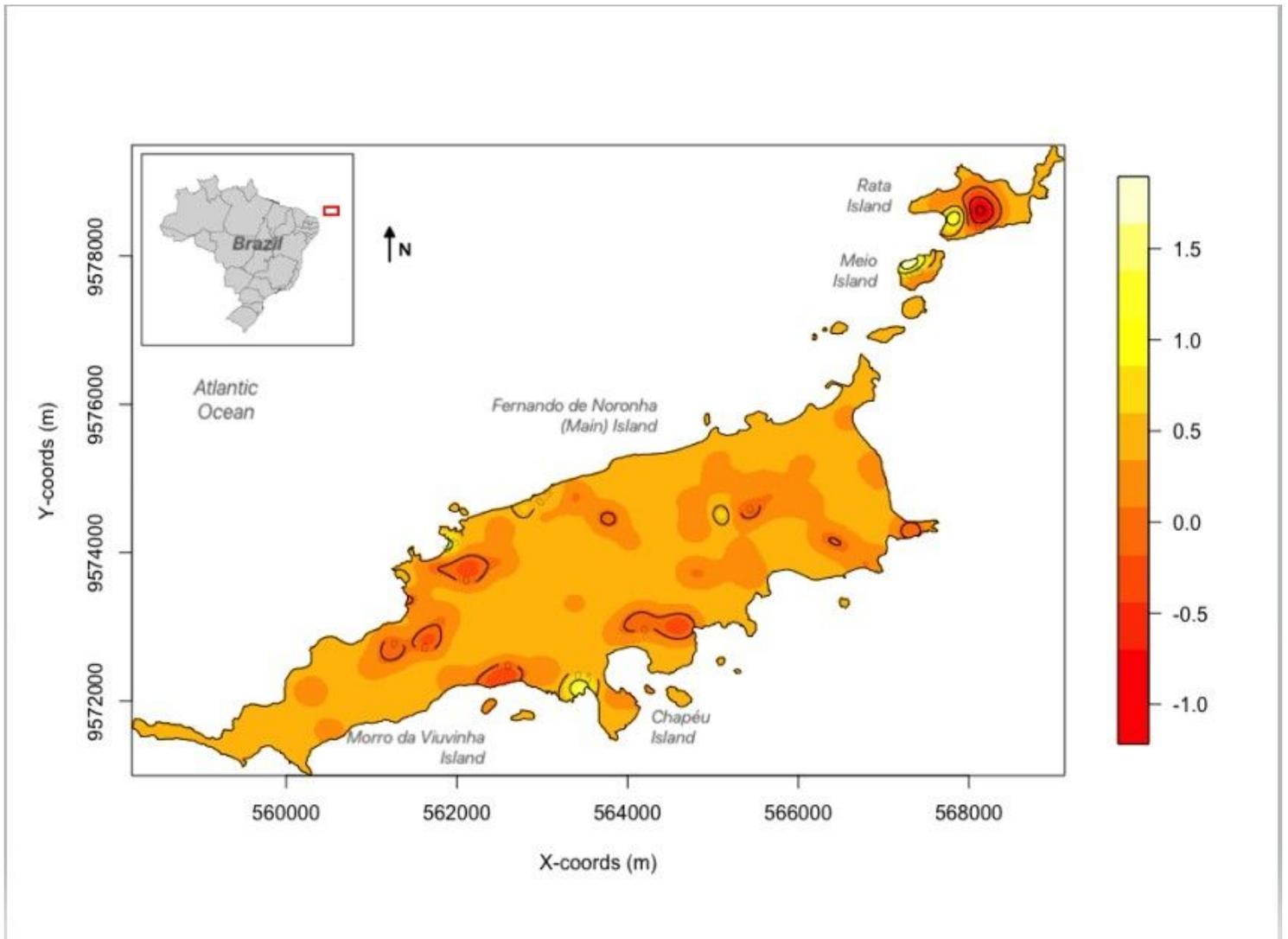


Figure 3

Density and distribution of the Noronha skink (*Trachylepis atlantica*) in Fernando de Noronha archipelago.