Population assessment of a novel island invasive: tegu (Salvator merianae) of Fernando de Noronha

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C.R. Abrahão[1,2], J.C. Russell[3], J.C.R. Silva[4], F. Ferreira[2] and R.A. Dias[2]

[1]National Center of Conservation of Reptiles and Amphibians, Instituto Chico Mendes de Conservação da Biodiversidade, Brazilian Ministry of Environment, Brazil. <carlos.abrahao@icmbio.gov.br>. [2]Laboratory of Epidemiology and Biostatistics, Department of Preventive Veterinary Medicine and Animal Health, School of Veterinary Medicine, University of São Paulo, Brazil. [3]School of Biological Sciences and Department of Statistics, University of Auckland, Private Bag 92019, Auckland, New Zealand. [4]Department of Veterinary Medicine, Federal Rural University of Pernambuco, Brazil.

ABSTRACT Fernando de Noronha is an oceanic archipelago in the Atlantic Ocean, 345 km offshore from the Brazilian coast. It comprises 21 islands and islets, of which the main island (FN) is 17 km^2 with a rapidly growing tourism industry in the last decades. Despite being a protected area and bearing Ramsar and UNESCO World Heritage site status, it is threatened by multiple terrestrial invasive species since its colonisation in the early 16th century. Invasive species and the increasing tourism contributes to a list of at least 15 endangered or critically endangered species according to IUCN criteria. The black and white tegu (*Salvator merianae*) is the largest lizard in South America, occurring in most of the Brazilian territory and reaching up to 8 kg and 1.6 m from head to tail. As an omnivorous and opportunistic lizard, it feeds on a variety of available items, including smaller vertebrates and eggs. The introduction of the tegu to FN as well as its immediate impact on local fauna were not recorded; however, its ongoing impact is expected to be high. We captured and marked 103 tegu in FN during the months of February and November of 2015 and 2016. We also counted animals by line-transect census in a sparsely inhabited and an uninhabited area of FN. Body size affected the capture probabilities, while season and sex had little or no effect. Densities estimated by capture-recapture in the sparsely inhabited area varied from 2.29 to 8.28 animals/ha according to sampling season. Line transect census in the same area revealed a density of 3.98 (±1.1) animals/ha and in the uninhabited area 13.83 (±3.9) animals/ha. Home range was 10.54 ha, ranging from 7.36 to 15.33 hectares. Tegu activity decreased in the months of July and August of 2015. Results from this study can assist conservation managers and decision makers to implement a science-based tegu management programme in the future.

Keywords: conservation, invasive species, lizard, oceanic island, reptile, *Salvator*, Teiidae, *Tupinambis*

INTRODUCTION

Islands are simplified ecosystems where each species plays an important role in its functioning (Simberloff, 1974). In these environments, the loss of a species and its functional role are not easily replaced, as would be the case in more species-rich ecosystems such as on continents. Despite corresponding to only about 5% of land area globally, islands contain more than 15% of terrestrial biodiversity (Tershy, et al., 2015). A lack of certain behaviour or life-history traits makes native insular species more vulnerable to the impacts of invasive species (Vitousek, 1988; Tershy, et al., 2015).

Introduction of invasive species is one of the major causes of contemporary biodiversity loss (Vitousek, et al., 1997; Chapin, et al., 2000). On islands, it is probably the major cause (Veitch & Clout, 2002; Reaser, et al., 2007). Direct and indirect competition, predation and introduction of diseases are some of the negative influences that invasive species can bring to native populations (Wyatt, et al., 2008; McCreless, et al., 2016; Russell, et al., 2017). Invasive predators are implicated in at least 58% of the worldwide contemporary extinctions for birds, mammals and reptiles (Doherty, et al., 2016). The insular ecosystem frailty combined with invasive species results in islands bearing 37% of all critically endangered species and 61% of all recorded extinct species, according to the IUCN Red List (Tershy, et al., 2015). Furthermore, the impact of invasive species is not constrained to local biodiversity, but also affects the economy, agriculture, health and human culture (Russell, et al., 2017)

Some invasive species, such as rodents, are globally widespread and their impacts on islands have been well described (Reaser, et al., 2007; Russell, et al., 2017). However, some invasive predators are only found regionally or locally and their impacts and management are not fully understood (see Eales, et al., 2010; Powell, et al., 2011). Those less well-known species must not be overlooked, as their impact might be equal to, if not larger than, common widespread invaders (Phillips, et al., 2007; Simberloff, 2009; Dorcas, et al., 2012; Neves, et al., 2017; Russell, et al., 2017).

Fernando de Noronha

Fernando de Noronha archipelago consists of 21 islands and islets, 340 km offshore from the northeast Brazilian coast. The total land area of the archipelago is 18 km^2 where the main island, also called Fernando de Noronha (FN) is about 16.7 km^2. The archipelago is a UNESCO world heritage site (since 2001) and has recently been named as a Ramsar site. Fernando de Noronha archipelago is an important breeding site for several species of birds, sea turtles and reptiles, some endemic and threatened with extinction (Sazima & Haemig, 2012; Reis & Hayward, 2013). At the moment, at least 22 invasive species of plants and animals are known in the archipelago (Sampaio & Schmidt, 2014).

The local economy is fundamentally based on tourism, with minimal production of goods and other services. The number of inhabitants on FN has increased substantially within the last decade due to a lack of control from Pernambuco State and the opportunities created by the growing tourism (Gasparini, et al., 2007). The total number of human inhabitants is debateable, with available information varying from two to five thousand people, with an additional up to three thousand tourists per year in the peak seasons (Andrade, et al., 2009; Marinho, 2016; IBGE, 2017; Pernambuco, 2017).

Urbanised areas are restricted to the main island, in the environmental protected area (APA), a protected area with sustainable use of natural resources – IUCN category

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VI – of approximately 8 km^2. The remainder of the main island, including the other islands and islets from the archipelago, is uninhabited and constitutes the National Park (PARNAMAR), where only indirect use is permitted – IUCN category II.

Tegu lizard

The black and white tegu lizard (*Salvator merianae* syn. *Tupinambis merianae*) (Fig. 1), hereby referred to as tegu, is the largest lizard in South America, up to 160 cm in total length and weighting up to 8 kg in its native range (Lopes & Abe, 1999; Andrade, et al., 2004). In their natural distribution in South America, tegu are commonly seen living and feeding close to inhabited areas, as well as forested areas (Oren, 1984; Sazima & Haddad, 1992; Bovendorp, et al., 2008; Winck, et al., 2011; Klug, et al., 2015; Muscat, et al., 2016). This omnivorous, opportunistic species feeds on fruits, vegetables, insects, small vertebrates, garbage and even carcasses when available (Sazima & Haddad, 1992; Kiefer & Sazima, 2002; Manes, et al., 2007; Bovendorp, et al., 2008; da Silva, et al., 2013; Muscat, et al., 2016). In South America, they can be found from south of the Amazon River to Argentina (Presch, 1973; Lanfri, et al., 2013; Passos, et al., 2013). In most areas where the tegu occurs, they are hunted for their skin and meat (Oren, 1984; Alves, et al., 2012), which has warranted the inclusion of the species on the CITES II appendix (UNEP-WCMC, 2014). In South America, adult females can lay up to 54 eggs per year (Donadio & Gallardo, 1984) and in captivity this species can possibly live up to 20 years (Brito, et al., 2001). The tegu is also considered an invasive species in Florida, where it is suspected to have a large impact on the already impacted local fauna (Pernas, et al., 2012; Mazzotti, et al., 2015).

Available data indicate that the tegu was deliberately introduced to the main island of Fernando de Noronha at the beginning of the 20th century (Santos, 1950), despite other publications suggesting a different period of introduction (e.g. Oren, 1984; Silva-Jr., et al., 2005). Whether to serve as hunting game or to help the control of rodents and toads, reasons for the introduction of tegu are speculative (Oren, 1984; Gasparini, et al., 2007; Ramalho, et al., 2009). Descriptions of FN fauna prior to the 20th century don't mention the tegu, despite mentioning the other endemic reptiles on the archipelago (Branner, 1888; Ridley, 1890). In the last century, very little was done to study the tegu population and impacts on the island ecosystem. Control or eradication methods were also never attempted, despite the management of the tegu being considered important to promote the conservation of endangered species living on the island (Brasil, 2004).

Fig. 1 Juvenile of *Salvator merianae* at Sancho Beach, Fernando de Noronha (photo: Vinicius Gasparotto).

We provide up to date information on the tegu population size and structure on Fernando de Noronha to contribute to an informed control programme to be undertaken by island conservation managers in the future.

METHODS

Study areas

To access the tegu population in the archipelago we selected two representative areas from the main island and visited the main vegetated islets that are used as nesting sites by resident birds. Land use in FN was simplified into three types, according to human usage: i) Densely inhabited areas, including hotels, houses and commercial buildings, paved streets and dense traffic, also with a higher density of uncontrolled dogs and cats; ii) Sparsely inhabited areas, including: rural areas similar to those found on the continent, and small villages with unpaved roads and sparse houses surrounded by crops and livestock animals. These two inhabited areas constitute most of the APA land; iii) Uninhabited areas, including areas of natural vegetation and secondary regeneration, with a few abandoned buildings and sporadic tourist usage. This area constitutes most of the PARNAMAR land (Fig. 2).

Within the inhabited areas, we chose the Boldró village that is a good representation of a sparsely inhabited area, with tourist visits, a small amount of commerce, paved and unpaved roads and houses of local workers. It is common to find domestic animals (dogs, cats, chickens), and crops and fruit trees in backyards. In the PARNAMAR we chose the southwestern Capim-açu region that represents the most intact? area of native vegetation on the main island (Mello & Adalardo de Oliveira, 2016). In Boldró village we performed a mark-recapture study and a line transect census study. In Capim-açu we performed a line transect census only.

Mark-recapture

To apply this method we chose the Boldró village located in a sparsely inhabited area of FN. This area is representative of the most common vegetation types on the main island and is subject to various levels of human interference while leaving space for native vegetation. Sampling seasons occurred during the years of 2015 and

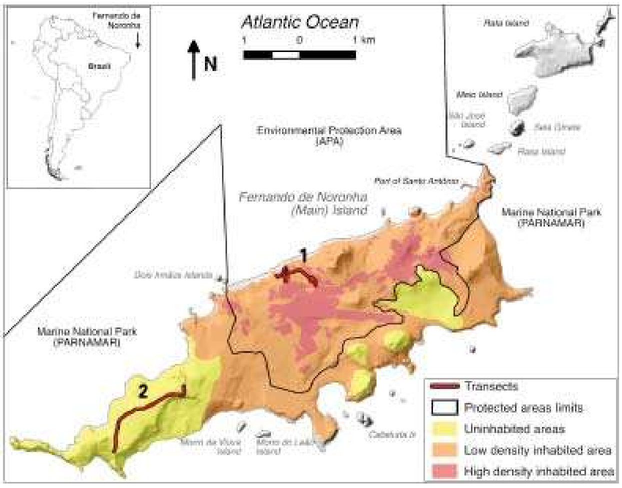

Fig. 2 Map of the protected areas of Fernando de Noronha Archipelago. Note: 1 is Boldró village transect, and 2 is Capim-açu transect (Land use layer by Vívian Uhlig – RAN/ICMBio).

2016, with 14 to 19 days of consecutive sampling in the beginning (Jan–Feb) and end (Oct–Nov) of the dry season. We opted to sample in the summer-spring as this species has been known to hibernate during the autumn-winter seasons on the continent (Andrade, et al., 2004; de Souza, et al., 2004).

We used ten funnel traps made out of PVC pipes (150 mm × 1 m) with one end closed. Those traps were placed in shaded spots next to vegetation borders, next to habitations, restaurants and areas that a tegu could use for hiding or foraging (Fig. 3). Each trap was placed in a stable position over trunks or stones in order to maintain at least a 20 degree angle to the closed end. The inclined position and lack of friction provided by the PVC material prevents animals from leaving the trap, where they remain until release. Raw chicken was used as baits and replaced every two days. Tegu locates the bait through smell (Yanosky, et al., 1993) and enters through the higher open entrance of the trap to get the bait that rests in the closed lower end of the pipe.

Traps were checked at the end of each day, when the individuals become inactive. Every animal was then restrained and marked with a transponder implanted subcutaneously. Snout vent length (SVL) was measured to the nearest 0.5 cm, with the use of a tape measure. The weight was taken using a Pesola® scale with a 10 g precision. Animals recaptured in the same season (e.g. less than 30 days interval) were considered to have the same weight and length, thus these data were collected only on the first capture of the season.

To estimate density (D) through mark-recapture data, we used the maximum-likelihood spatially explicit capture-recapture (ML SECR) package from R (Team, 2000; Borchers & Efford, 2008). We assumed a Poisson distribution of range centres (i.e. random) with a half-normal curve detection function parameterised by g_0 (probability of detection when trap and range centre coincide) and σ (spatial scale of the detection function). Removals from the population (i.e. poaching or death) are assigned known capture histories of 0 with probability equals 1 following death. The conditional likelihood was used to derive density, incorporating individual covariates of SVL and sex. Models were compared using an AIC framework, but due to sparse data, subsets of models on σ and then g_0 were considered independently. The area of capture exposure, which usually would be related to an individual's home-range, was approximated by a 95% circular probability density area of capture as:

$$HR_{95} = \pi(2.45\sigma)^2$$

Fig. 3 PVC Funnel trap to catch tegu mounted near a tree at the edge of a clearing.

Line-transect census

Two tracks were chosen to undertake the census counting (Fig. 2). One in the Boldró village, 1,820 m in length, to make possible comparisons between density methods in the same area, another in the Capim-açu track, 2,000 m in length, to make possible a comparison between a sparsely inhabited area and uninhabited area. A trained volunteer walked each track counting tegu in the high activity hours (10 a.m. to 2 p.m.). For six days, the Capim-açu track was walked in one direction and after a 30 min break at the farthest point, it was walked back. Atypical days with rain, temperatures below 25°C or excessive wind were avoided to prevent weather interference on abundance data. Counting along Boldró track was repeated nine times and Capim-açu 35 times during this study. When a tegu was sighted, the observer took the perpendicular distance of the animal from the centre of the track using a scale tape, to the nearest 0.5 m and up to 20 m distance. Any tegu sightings over 20 m of distance were discarded, but the thick vegetation in this region prevents seeing animals in the vegetated area on the transect borders.

We calculated the density of animals along the transect using distance sampling analysis, but zero spiking in the data (excessive observations close to the line) violated basic premises, likely due to a much higher level of detection, and potentially tegu abundance, along the clear open tracks in the dense forest. We subsequently used the line-transect census methodology (Burnham, et al., 1980; McDiarmid, et al., 2012) on a subset of the data, for observations directly on the open track only. Total number of individuals observed along the line-transect were used to represent the abundance on the track area, assuming every individual within the transect was observed. The area was calculated by using the average width of the track (measured every 100 m) and then multiplied by its length. Open areas were not measured and were assumed to have the same average width as the forested areas. Only animals observed within the established width of the track (e.g. clear area) were considered for such analysis.

We used a two-tailed t-test with unequal variances to compare daily density data between Boldró and Capim-açu. Only the high activity months (Feb–Jun, Sep–Nov) were used for this comparison, since we did not have data from the dry season in the Boldró area. The same method was used to compare densities observed on Capim-açu in the high activity months and low-activity months (Jul–Aug). To coarsely calculate the total abundance of tegu in FN, we stratified the map according to three main land uses: i): densely inhabited areas (226 ha); ii) sparsely inhabited areas (960 ha), and iii) uninhabited areas (417 ha) (Fig. 2). Average density and ranges from Capim-açu line-transect counts were used to estimate the abundance of tegu in the uninhabited areas of FN. The same method was used in Boldró to estimate the abundance of tegu in the sparsely inhabited areas of FN. Densely inhabited areas and areas with no vegetation (e.g. beaches, sand dunes and rocky areas – 97 ha) were excluded from the abundance calculations for they were not represented in the study area and were considered poor tegu habitat.

Islet surveys

We visited seven of the larger vegetated offshore islets of the archipelago (Rata, Rasa, do Meio, Conceição, Morro Dois Irmãos, Morro da Viuvinha and Morro do Chapéu) at least once during the study period (Fig. 2). We spent from one to twelve hours actively searching on each islet, searching for sightings or indirect signs of tegu presence (tracks or burrows). We also inquired with local inhabitants and other researchers for records of tegu presence on the other islands, since tegu can swim and also could have been brought to other islands intentionally in the past.

RESULTS

In the mark-recapture study we had a total of 190 captures over 69 trapping days in the Boldró village. From the 190 captures, we captured 103 unique individuals with 87 recaptures. Of the ten traps installed, two had to be moved in the last sampling season to avoid interference by people. These traps remained a total of 55 days in the first location and 14 days in the second location, less than 50 m away from where they were previously placed. Since tegu weight and size (SVL) were highly correlated (R^2=0.84), we have chosen only SVL as a covariate on σ and g_0. SVL also provides a better measure than total length, for it excludes the tail that can be lost or be regenerated to a variable size. Given the relatively low number of recaptures, we had to specify reasonable starting values for the likelihood maximisation with starting values of $g_0 = 0.1$ and sigma = 50 from a preliminary inspection of the data.

Ranging behaviour and probability of capture

We first fitted and ranked models combining the influence of sex and size on the ranging behaviour (σ) of the animals, while keeping a fixed capture probability (g_0). The simplest model, with fixed probability of capture and fixed ranging behaviour had 91% support, showing that size has no effect on the ranging behaviour of animals, while sex has little effect (Table 1).

Based on the best adjusted model for ranging behaviour, we kept σ constant across sessions and tested the influence of sampling period, sex and size on the probability of capture of the individuals. As seen in Table 2, the model including SVL had 44% support showing that body size as a continuous variable is the most important of the tested covariates to affect the probability of capture. Session also showed some importance in explaining the variation as seen in models 2 and 3.

Home-range

To produce real estimates for capture probabilities (g_0) and ranging behaviour (σ), we took the model including the most important covariates (session and size), for probability of capture and fixed ranging behaviour. The average size (SVL) used in the estimates was 30.2 cm (Table 3).

Based on real parameters obtained from the chosen model, we calculated 95% home ranges (HR_{95}) for average size and both sexes as 10.54 ha, ranging from 7.26 to 15.33 ha.

Density, abundance and activity

Finally, we estimated densities and sampled areas for each sampling season over the chosen model (Table 4).

In the line transect study, the Boldró transect (0.419 ha) was surveyed six times in the high-activity months (Nov 2015 and Feb 2016), with a total linear effort of 10.92 km. Only ten animals were sighted in this transect within the established transect width of 2.3 m during the period of study. The calculated density for Boldró is 3.98 (±1.1) animals/ha. The Capim-açu transect (0.492 ha) was surveyed 35 times from February 2015 to February 2016, with a total linear effort of 70 km. In this transect, 260 animals were sighted within the established average width of 2.46 m during the study. The calculated density for Capim-açu is 13.83 (±3.9) animals/ha.

Densities calculated using the line transect method were different between Boldró village and Capim-açu transects (t=6.45, P≤0.00001). There were no surveys in the Boldró transect during the low-activity months, thus, only densities from high-activity months in both transects were used to compare the densities averages from different areas. In Capim-açu, densities also differed between high-activity months and low-activity months (t=3.29, P≤0.01). The number of sightings on each occasion for Capim-açu transect is shown in Fig. 4 where a decline in number of sightings can be seen in the months of July and August.

To estimate the abundance of tegu in FN we used the calculated uninhabited area of FN as being 417 ha and the total sparsely inhabited area of FN as being 960 ha (see Fig. 2). Considering Capim-açu transect densities, calculated abundances range from 4,141 to 7,393 tegu in the uninhabited area. Using densities from Boldró transect for the sparsely inhabited areas, we estimated abundance from 2,765 to 4,877 tegu in that area. Total number of animals estimated for both calculated areas is from 6,906 to 12,270 tegu. High-density inhabited areas and non-vegetated areas of the island (463 ha) were excluded from this calculation for they were not represented in the samples; however, tegu are expected to be using those areas in a lower rate, thus abundance results should be taken as an underestimation of the whole population.

Population parameters

Males constituted the majority of the sampled population in all but the first sampling period. Males were also larger and heavier than females in all sampled periods. Male weight ranged from 400 g to 2,450 g and female weight ranged from 600 g to 1,940 g. Snout–vent (i.e. body) length for males ranged from 24 to 40 cm and for females from 26 to 36 cm. Averages and range by season and sex are given in Table 5.

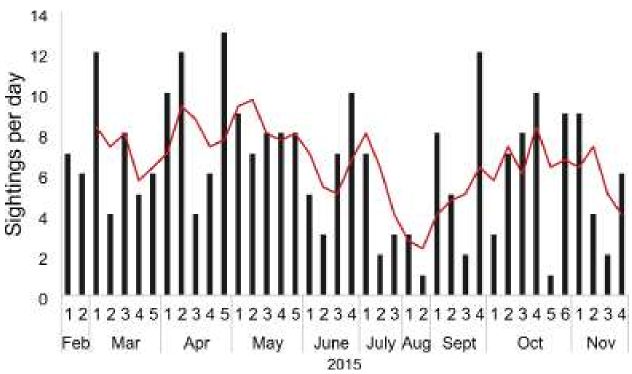

Fig. 4 Number of sightings of tegu in the Capim-açu transect during the 2015 sampling period. The line represents a moving average of three samples.

Table 1 Model results of tegu detection function for covariates of the scale parameter (σ) and the probability of capture equal to the home range centre (g_0).

σ Models	Detection function	Npar	Log likelihood	AICc	Rank	Weight %
sigma~1	Half normal	2	-609.159	1,222.411	1	91%
sigma~sex	Half normal	3	-610.382	1,226.950	2	9%
sigma~SVL	Half normal	3	-766.307	1,538.800	3	0%

Table 2 Best adjustment on models tested for constant probability of capture (g_0) with covariates as sampling size (SVL), sex, season (session) and ranging behaviour (sigma).

g_0 Models	Detection function	Npar	Log likelihood	AICc	Rank	Weight %
g_0~svl	Half normal	3	-605.896	1,217.978	1	44.26
g_0~session + svl	Half normal	6	-602.833	1,218.333	2	37.06
g_0~session	Half normal	5	-605.242	1,220.957	3	9.98
g_0~1	Half normal	2	-609.159	1,222.411	4	4.82
g_0~sex + svl	Half normal	4	-608.020	1,224.353	5	1.83
g_0~session + sex + svl	Half normal	7	-605.046	1,224.988	6	1.33
g_0~sex	Half normal	3	-610.016	1,226.219	7	0.72
g_0~session + sex	Half normal	6	-608.184	1,229.034	8	0

Table 3 Estimates of real parameters for σ and g_0 in each sampling season, using average size of 30.2 cm SVL. Given standard errors and 95% confidence intervals (lower class and upper class).

Real parameters SVL=30.2	Estimate	SE	lcl	ucl
g_0 Feb/2015	0.012	0.006	0.004	0.033
g_0 Nov/2015	0.035	0.010	0.019	0.062
g_0 Feb/2016	0.032	0.011	0.016	0.062
g_0 Nov/2016	0.039	0.010	0.023	0.064
σ	74.780	7.148	62.030	90.150

Islets

From the seven visited islets of the archipelago, only Rata Island had indirect records of the presence of tegu. There was an effort of 58.5 person-hours of active searching, plus 72 trap-hours divided among three visits to Rata Island, but no direct sights or captures were made. Tracks, faeces and burrows were found, indicating the presence of tegu, possibly at a lower density than the main island.

DISCUSSION

Policy makers, managers and the general public need to be informed of the consequences of invasive species in order to manage their impacts. Understanding the population biology of an invasive species is a first step to acquire essential information for management decisions that may alleviate impacts. Despite Fernando de Noronha being inhabited since the 16th century, very little has been done to understand or prevent the impact of invasive species on endangered and endemic species that struggle to coexist in the archipelago (Sampaio & Schmidt, 2014; Mello & Adalardo de Oliveira, 2016; Dias, et al., 2017).

Ranging behaviour and probability of capture

Spatial detection models show that size and sex had little influence on tegu ranging behaviour on FN. Klug, et al. (2015) found that size differences were not likely to be contributing to movement differences for tegu. In a subtropical coastal region on southern Brazil, Winck, et al. (2011) found tegu to be more active when temperatures start rising by the end of spring and early summer. They also related peaks of activity while males were dispersing and after the emergence period, to be due to the beginning of foraging and sexual activity. The present study does not capture full seasonal variation because of time-constrained sampling, but a drop in activity was observed in July and August, as observed in other tegu studies (Winck & Cechin, 2008; Tattersall, et al., 2016). This small window of low activity of tegu on FN may not promote a significant variation in relation to the impacts it causes to other species. On the main island, only masked booby (*Sula dactylatra*) still nest on the ground in a small peninsula next to the end of Capim-açu track. Their eggs are laid in the first months of the year as observed by e Silva & Neves (2008) on secondary islands of the archipelago. The Noronha skink (*Trachylepis atlantica*) is also a common prey item in the tegu diet. Despite being relatively abundant, nothing is known about its reproduction. It is thought to reproduce throughout the year as for *Trachylepis sechellensis* on the Seychelles, another tropical archipelago (Bringsøe, 2008). Sea turtle nests are also preyed upon by tegu, as recorded by TAMAR project for *Chelonia mydas* on FN (Bellini & Sanches, 1996; e Silva & Neves, 2008), including predation of hatchlings (Ayrton K. Péres-Jr, pers. comm.). Turtles on FN nest from January to June, when tegu are active.

For the probability of capture, size was an important determinant, but population studies using traps often fail to collect a broad representative sample of the population as seen in Carter, et al. (2012). A hole of 3 cm diameter was made in the closed end of the pipe to avoid flooding of the trap and unwanted capture of native lizards. This safety measure may bias the sample as it allows small animals to escape. These animals would possibly not be able to be marked by transponder implant and thus were of less importance for this study in any case. Behavioural traits such as niche separation due to intraspecific competition could also explain a size interference on capture probabilities (Herrel, et al., 2006; Siqueira & Rocha, 2008). The observed small influence of season on capture probabilities is primarily in the first session and possibly due to adjustments of methodology following that

Table 4 Densities and estimated sampling areas in Boldró village for each season sampled derived from the best adjustment models.

Period	Density/ha	Std. Error	Min (95%)	Max (95%)	ESA
Feb/2015	4.19	0.93	2.72	6.44	7.40
Nov/2015	4.45	0.94	2.95	6.71	7.42
Feb/2016	3.59	0.84	2.29	5.64	7.52
Nov/2016	5.07	1.05	3.39	7.59	8.28

Table 5 Tegu sex, size and weight averages with ranges in each sampling season.

Period	Sex	n (%)	$\bar{x}$ SVL (cm)	SVL range	$\bar{x}$ Weight (g)	Weight range
Feb 2015	M	15 (42)	33.58	29–37	1,491.00	875–2,175
	F	21 (58)	31.22	28–36	1,051.67	640–1,940
Nov 2015	M	21 (60)	32.26	28–39	1,347.14	740–2,240
	F	14 (40)	29.35	26–33	965.00	600–1,550
Feb 2016	M	18 (55)	33.28	28–37	1,368.89	660–1,930
	F	15 (45)	30.40	27–34	914.67	600–1,590
Nov 2016	M	47 (68)	32.53	24–40	1,294.26	400–2,450
	F	22 (32)	30.67	26–35	1,030.45	600–1,560

first sampling season. A variation in capture probabilities is not expected once sampling seasons were chosen within the high-activity periods for tegu.

Home-range

In the tegu natural distribution, older males have larger territories, while juvenile males and females have smaller territories with higher overlap. A peak of activity in males was observed at the end of the low-activity period (Winck, et al., 2011). A decrease in home range after the mating season was also observed in the El Palmar National Park, in Argentina (Fitzgerald, et al., 1991). Results from this study suggest little influence of sex on tegu capture in traps. Since SECR only estimates spatial exposure area to traps, sex could be affecting the ranging behaviour of tegu in FN but this method is not precise enough to detect such variation. This result may also have been affected by biases in the capture probability of certain tegu size classes (i.e. juveniles).

Lirio, et al. (2004) tracked six radio-implanted tegu in FN and estimated home-ranges varied from 0.73 to 7.8 ha (3.3 ha on average). The authors also comment that a gravid female was used in the study, representing the smallest home-range, and that the activity centre was usually close to the shelter. Winck, et al. (2011), found home-ranges from 0.05 to 26.4 ha for a continental population in southern Brazil. Home-ranges as measured in the present study are within the previous findings for the natural distribution of tegu and are a little higher than those described by Lirio, et al. (2004).

Since σ did not differ between sexes, estimated home-ranges were considered the same for males and females. Home-ranges can provide necessary information to set management on invasive species, such as the density of control devices (Hays & Conant, 2007; Howald, et al., 2007; Anderson, et al., 2016). For continental tegu, behavioural traits such as season, age and reproductive status can be implicated in home-range variation (Winck, et al., 2011). In FN, factors such as the lack of competitors, predators and resource availability could be also influencing tegu home ranges (Ballinger, 1977; Shine, 1987; Novosolov, et al., 2016). With an average home range (HR_{95}) of 10.54 ha, tegu on FN are quite mobile. This behaviour allows them to look for resources in a vast area and feed even when resources are not abundant (e.g. dry season). We also noticed an overlap of territories throughout the year, as juveniles forage together and coexist with adult males and females in the same area. Only youngsters seem to avoid larger tegu, having more secretive habits. In general a large home range also increases the probability of a species being exposed to a control method (Howald, et al., 2007). That means managers might need fewer traps (e.g. one every few ha) in order to control tegu on FN.

Density, abundance and activity

In Boldró village, density estimates from capture-recapture ranged from 2.29 to 7.59 animals/ha while estimates from the line transect census ranged from 2.88 to 5.08 animals/ha. Those densities are much higher than the 0.83 animals/ha observed for a tegu population living in Anchieta Island or the 0.63 animals/ha as seen in the Espírito Santo Atlantic rainforest, both in south-eastern Brazil (Bovendorp, et al., 2008; Chiarello, et al., 2010). These higher estimates could be due to a tropical climate in FN that favours reptiles with a low variation in temperature over the year. Abundance of resources and the lack of natural predators can also contribute to the higher density observed in FN as seen for other island invasive predators (Pekelharing, et al., 1998; Hays & Conant, 2007; Ferreira, et al., 2012).

Since density estimates from both methods used in this study (line transect census and mark-recapture) were similar, we opted to use values from the line transect census because it also provided density for the Capim-açu transect. Density from those transects was applied to the region represented by each transect to obtain abundance for both represented areas. There is a possible error associated with the extrapolation of the transect densities over the whole area, especially to areas with dense vegetation, as observers may find a higher number of tegu using the open areas, causing an overestimation of density. However, a similar density estimated by two different methods supports the idea of transect counts being a reliable method, despite the associated error. An estimate of abundance can help management decisions in quantifying the effort and costs required to control or eradicate (Holmes, et al., 2015; Keitt, et al., 2015). Density estimated in Capim-açu was higher than that estimated in Boldró and a broad list of factors could explain such differences, the most important are discussed here.

Animals are not distributed uniformly in the environment and they tend to occupy environments that seem more favourable, while less favourable habitats are occupied in lower densities (Diaz & Carrascal, 1991; Fraga, et al., 2013). In FN, presence of predators and competitors, such as cats, could negatively affect tegu populations by preying on juveniles and hunting other potential prey of tegu such as rats and other reptiles. In Boldró village and other high-density inhabited areas of the island, the influence of cats is higher, since the cat population is denser when closer to inhabited areas (Dias, et al., 2017). Dogs also inhibit presence of tegu by chasing and killing tegu when they cross territories, making inhabited areas again less suitable for tegu (C.A. pers. obs.).

Tegu are appreciated for their meat in the northeast of Brazil, where the species can be a delicacy and an important source of protein in poor communities (Mendonça, et al., 2011; Nóbrega Alves, et al., 2012). Poaching of tegu in FN is driven by different reasons, with tegu being commonly hunted by poultry farmers when they break into henhouses to eat eggs and chicks. Hunting in FN is done with fishing line and hooks, baited with fish or chicken, in the areas close to residences (C.A. pers. obs.). Tegu abdominal fat is also widely known as a medicine and is used by locals to treat sore throat, earache and other ailments (Nóbrega Alves, et al., 2012). Those properties are scientifically based since the anti-inflammatory properties of tegu fat has been proven (Ferreira, et al., 2010).

Tegu are generalists and feed on any available resources, including vegetation, fruits, insects, vertebrates and eggs (Vanzolini, et al., 1980; Kiefer & Sazima, 2002; Mourthé, 2010). Those adaptations do not restrict resources for the tegu population in FN, where it possibly lives with plenty of food throughout the year. A reduction in the tegu population is more likely to be present in human altered environments such as densely inhabited areas, with negative effects of domestic animals and poaching, despite a possible higher availability of food (crops, fruit trees and rubbish). Another factor that could be affecting the results is of behavioural origin. The negative impact of human presence seems to make the tegu population shift towards uninhabited areas that offer better habitat with less interference and still plenty of resources. Despite density underestimation being a possibility when failing to observe all animals on the transect (e.g. behaviour to avoid human contact in inhabited areas), the more intensive mark-recapture study showed similar estimates of density thereby disproving a possible methodological interference.

Population parameters

Size in this study was inferred by SVL and was also closely correlated to weight. Although, size can be affected by external factors when trying to infer individuals' ages (Halliday & Verrell, 1988; Adolph & Porter, 1996), weight can also reflect body condition and be influenced by the loss of the tail, a common finding in the FN population. Size can be related to sexual maturity (Fitzgerald, et al., 1993), while movement and home-ranges can be affected by sex and reproductive status (Winck, et al., 2011). Size is also related to reproductive capacity of females (Fitzgerald, et al., 1993). Tegu on FN seem to be smaller than those found in continental South America, thus, the female reproduction index in FN should be lower than in the continent (Fitzgerald et al., 1991; Winck et al., 2011). The smaller size on FN can also be related to a much higher density caused by lower competition and predation rates than the ones found in the continent (Novosolov, et al., 2016).

Males seem to be a higher fraction of the population on FN, which might influence reproduction and population growth (Le Galliard, et al., 2005). Sex ratio can be affected by average temperature (e.g. natality rates) or by any factor that increases mortality rates in only one of the sexes. Populations of tegu in Paraguay were consistently male-biased (Mieres & Fitzgerald, 2006), possibly leading to a higher fecundity rate of females or having a negative effect on lizard populations as observed by Le Galliard, et al. (2005).

Islets

Tegu are good swimmers and there are various sightings from local residents of tegu swimming or diving near to the main island. A video made by Elias Pereira and Nelly Burella shows a juvenile tegu voluntarily swimming across Baia dos Golfinhos, on the main island. Other than swimming, tegu could have been taken to other islands in the past for the same reason they were taken to the main island (either to control rats or serve as a food supply). Manoel P. dos Santos, who lived on Rata Island until 1986, says tegu were abundant there during that time. It seems that after his family left Rata, the population of tegu has decreased. However, the island seems to be big enough to maintain a small population of tegu. Some animals might also occasionally swim to other islets, but even a single animal could hardly live for long on the scarce resources available on those smaller islands, forcing them back to the main island.

Future steps

The reasons why the tegu was introduced to Fernando de Noronha, when it happened and the impacts this predator has caused to the archipelago were not documented and remain unknown. However, the understanding of impacts caused by invasive predators in islands worldwide provides sufficient evidence that management is required in order to protect local biodiversity. Eradication is usually the best option when the tools are available, but when they are absent, control measures may be better than the do-nothing approach (Fletcher, et al., 2015; Russell, et al., 2017).

On Fernando de Noronha, managing the impacts of tegu over native fauna is already on the list of priorities, as documented in the management plan of the APA (Brasil, 2004). However, providing up to date information on tegu population structure and biology in FN is expected to contribute to the implementation of a science-based invasive species programme in the future. Based on results from this work and field experience of the authors in FN, our contribution to this programme is offered here as a suggestion to local managers and decision-makers.

Measures of tegu control in FN should be placed in strategic locations where impacts on native fauna are considered higher, such as ground nesting sites for birds, nesting beaches for turtles and most preserved vegetated areas for other reptiles, crabs and even invertebrate fauna. Live or kill traps could be used, depending on the destination identified for the animals. Traps like the ones used in this study proved to be very efficient for adult tegu and seem very cost-effective. Considering the relatively high probability of capture observed, live traps needs to be checked at least once a day. Traps also need to be placed in the shade as lizards are easily prone to overheating in the tropics. Traps can be baited with eggs, bacon, chicken, fish or any other scent-driven attractant, since smell is the main sense for area exploration of tegu.

Considering the very high density of animals, an equally high number of traps should be required (one per ha or more). Control areas can be fenced by a tegu-proof fence to prevent quick reestablishment of the population by recruitment of juveniles. Traps should be placed preferentially in transition areas between vegetated and clear areas, where tegu transit to control body temperature during times of higher activity. Management effort should be stronger after the low-activity period, up to the end of the reproduction season (expected to be from September to March in FN). However, since there are animals active throughout the year, effort should also be made according to the reproduction of potential prey species such as the ground-nesting birds, sea turtle nests and crab spawning period. Control effort is expected to be up to four times higher in the uninhabited areas than in the inhabited areas of FN, given tegu density variation between those areas.

There are no specific tools available to control tegu and poison should not currently be considered as an option, since it would also threaten other endemic reptiles in FN. Hunting also requires special firearm permits and doesn't seem to be an option when in a tourist location like FN. For the moment, only fencing and trapping seem to be feasible solutions to manage tegu impacts on the archipelago's biodiversity.

CONCLUSION

Some invasive species are not commonly widespread and attract little attention of researchers. However, once established, those species can pose a real threat to native biodiversity (Simberloff, 2009; Neves, et al., 2017). Tegu have been established on FN for a century (Santos, 1950), but their population structure and impacts on native fauna remained understudied. This assessment provides focal information for a future control programme of tegu on Fernando de Noronha archipelago. We also aim to contribute to a larger ongoing process in Brazil, where invasive species move towards being a primary problem to be addressed for biodiversity conservation. Finally, we call on researchers worldwide to focus on other neglected invasive insular species as they represent a challenge and a frontier for island conservation.

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