



Anthropogenic habitat modification linked to deformities in Cururu Toads from Fernando de Noronha

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Manuscript received: 20 January 2021

Accepted: 7 June 2021 by ALEXANDER KUPFER

Abstract. Body deformities are often linked to environmental disturbances when the proportion of affected individuals exceeds 10% of the population. Thus, amphibians can help improving both ecosystems and human welfare. We studied a potential cause of deformities in an introduced population of toads on a Brazilian island where the prevalence exceeds 50%. We inspected individual toads for external and internal morphological anomalies and tested for links between anthropogenic habitat disturbance and the frequency of deformities. We then compared deformity data from the Fernando de Noronha Islands with data from other invasive toad populations in the USA, the Bermudas and Brazil, recording novel deformities and summarizing historical trends of its prevalence over the past decade. We furthermore investigated partial and total blindness, and found strong evidence that eyes are lost during the post-metamorphic stage (adulthood) rather than being an innate deformity. High concentrations of environmental pollutants in more urbanized areas on Fernando de Noronha have likely led to increased anomalies in toads sampled from highly disturbed habitats. We discuss other potential causes that may be acting synergistically to drive one of the highest rates of deformities observed in vertebrate populations.

Key words. Abnormality, Amphibia, Anura, Bufonidae, *Rhinella*, Fernando de Noronha archipelago, human interference, island.

Introduction

Body deformities afflicting amphibians have been reported globally. Commonly, these deformities occur naturally in wild populations, but when local prevalence crosses a ~ 10% threshold, external factors are suggested to be playing a key role driving deformities (LANNOO 2008). In this context, intrinsic and extrinsic factors have been suggested as the underlying causative agents. Among the most important ones are environmental chemical pollution (HELGEN et al. 2000, BACON et al. 2013), radioactivity (HENLE et al. 2017a), high parasite pressure in the invasive range (JOHNSON et al. 2002, HENLE et al. 2017b), or even inbreeding depression (although the latter has never been thoroughly assessed as a direct causal factor for amphibian deformities: WILLIAMS et al. 2008). For instance, in an introduced population of Cane Toads, *Rhinella marina*, in Bermuda, deformities were recorded in about 23% of the individuals (BACON et al. 2006), and experimental data indicated that a synergistic effect of chemical contamination and ultra-

violet radiation was the underlying cause of these deformities (BACON et al. 2013). Several other anuran populations also exhibit high prevalences of deformities (e.g., JOHNSON et al. 2001, GARCÍA-MUÑOZ et al. 2010, MACHADO et al. 2010), although the underlying causes remain obscure.

In Brazil, several insular populations of toads (species of the genus *Rhinella*) have been reported as exhibiting high frequencies of deformities. Examples include *R. marina* from Bailique Island, state of Amapá (BESSA-SILVA et al. 2016), *R. ornata* from the islands of Ilha Grande, Marambaia and Itacuruçá, state of Rio de Janeiro (REBOUÇAS et al. 2019b), and *R. diptycha* (postmetamorphs and tadpoles) from the archipelago of Fernando de Noronha, state of Pernambuco (TOLEDO & RIBEIRO 2009, TOLLEDO et al. 2014, FORTI et al. 2017, MICHELETTI et al. 2020). On the islands of Rio de Janeiro and Amapá, one in every three sampled toads shows deformities (Supplementary Table S2) (BESSA-SILVA et al. 2016, REBOUÇAS et al. 2019b). On the main island of Fernando de Noronha, however, about one in every two toads is deformed to some degree (TOLEDO &

RIBEIRO 2009), with many individuals being partially or totally blind (TOLLEDO & TOLEDO 2015) and some being deaf (COBO-CUAN et al. 2020). Although Fernando de Noronha is among the sites with the highest prevalences of amphibian deformities globally (TOLEDO & RIBEIRO 2009), its causes remain to be revealed (TOLLEDO et al. 2014).

Deformities in *R. diptycha*, the Cururu Toad, from Fernando de Noronha are diverse, ranging from oral disc disarrangements in tadpoles (TOLLEDO et al. 2014) to lack of legs, fingers and eyes in adults (TOLEDO & RIBEIRO 2009). Since the first studies were performed, the understanding of anuran anomalies has advanced (e.g., HENLE et al. 2017a, 2017b, 2017c). However, some of these deformities observed in Fernando de Noronha have never before been observed and reported from other populations in Brazil or elsewhere (Supplementary Table S1). Deformities are commonly classified based on external examination, which limits the evaluation and excludes the observation of other internal or less-evident deformities. Thus, the use of more sophisticated techniques (i.e., CT-scans) can highlight aspects not previously observed. Interestingly, eye-related anomalies have been reported in high prevalences for Fernando de Noronha toads, ranging from abnormal iris conformation to total blindness, both with and without important ecological consequences (TOLLEDO & TOLEDO 2015). However, the leading causes of these anomalies have not been previously investigated. Thus, this study aims to (i) review the classification of deformities and describe novel deformities in Cururu Toads from Fernando de Noronha using other methods, such as CT-scans and dissection; (ii) investigate further the processes that might lead to anophthalmia in a subsample of the population, as ~ 20% of individual toads present some level of eye anomaly (TOLLEDO & TOLEDO 2015); and (iii) test whether these deformities could be linked to anthropogenic habitat disturbance, which could provide insights into the potential impact of environmental stress on deformities in amphibians.

Material and methods

Field sampling

We evaluated individuals of the Cururu Toad, *Rhinella diptycha* (Anura, Bufonidae), from the archipelago of Fernando de Noronha sampled during expeditions between 2008 and 2019. Individuals were collected by means of active searches, and were checked for any deformities. Active searches were performed to avoid sampling bias favouring individuals with anomalies that could be more vulnerable to capture. Snout–vent length (SVL) was measured with a calliper (to the nearest 0.01 mm) and sexing was done based on the presence/absence of vocal sacs and nuptial asperities that are known as secondary sexual characteristics present only in males (e.g., REBOUÇAS et al. 2019a), and during necropsy, by examination of gonad maturation. During the necropsies, we recorded all external and internal deformities described below. We CT-scanned ten of our sampled toads with external and visible anomalies for

more detailed descriptions of their skeletal anatomy (see Supplementary material). We used a Skyscan micro CT Scanner model 1176 at 240 kv, and reconstructions were performed with the software NRwcon 1.6.6.0. After examination for anomalies, all individuals were released at their original collection sites, while those used in CT-Scan and dissection had been collected in previous studies (see TOLLEDO & RIBEIRO 2009, TOLLEDO & TOLEDO 2015).

In addition to sampling toads in Fernando de Noronha, we sampled Cane Toads, *Rhinella marina*, in Bermuda in 2016 and estimated the frequency of deformities in our focal population, based on external examination. We also analyzed all available specimens of *R. marina* from Hawai'i and were able to estimate deformity prevalence among individuals collected in 1982 and 2015 (see Appendix). All those individuals were in the collection of the University of Hawai'i, Honolulu. We used these data in addition to publicly available data on *Rhinella diptycha* from Fernando de Noronha and two mainland sites (TOLEDO & RIBEIRO 2009) plus available data on *R. marina* from Bermuda (BACON et al. 2006) to identify trends of deformities among introduced bufonids. Finally, we updated the previously classified anomalies reported by TOLEDO & RIBEIRO (2009), and some of the deformities observed in Bermuda toads were reclassified in the Fernando de Noronha dataset to allow for proper comparisons between these two islands (Supplementary Table S1).

Anthropogenic habitat disturbance

To investigate whether anthropogenic habitat disturbance is correlated with the frequency of anomalies in amphibians from Fernando de Noronha, we quantified the degree of habitat disturbance for each of our sampling sites using the satellite imagery from 2015 available from Google Earth Pro (GOOGLE 2020). Specifically, we extracted percentage data on non-natural land cover within a zone of 300 m around the edges of our 11 focal ponds using Arc Map 10.6.1 (ESRI 2018) (Fig. 1). If part of the surrounding area was made up by sea water, we compensated this area with adjacent land. This metric is similar to ecological footprinting, which estimates the amount of land necessary to support an ecological unit, such as an individual, population, product or activity (SANDESON et al. 2002). Here we calculated the proportion of clear non-natural vegetation cover (modified by human activity), such as housing, farming, clearcuts or roads, as disturbed habitat.

Statistical analyses

We performed Generalized Linear Modelling (GLM) with binomial distributions and logit links to evaluate the strength of the following predictive variables that might explain the proportion of deformities: snout–vent length (SVL), to verify if larger individuals present more deformities, sex (% males), to verify if one sex might be more

prone to deformities, and anthropogenic habitat disturbance (% disturbed), to verify if deformities are related to human interference. To verify the best explanatory model, we ranked all possible models based on the Akaike Information Criterion (AIC) through the “dredge” function of the package “MuMIn” (BARTON 2020), and we selected the most parsimonious model according to ΔAIC . In order to verify multicollinearity among variables, we used the Variation Inflation Factor, performed through the function “vif” in the package “car” (FOX & WEISBERG 2019). This index is used to verify cross-correlations between explanatory variables, and when it is higher than a threshold, here considered as $VIF = 4$ (HAIR et al. 2010), there is multicollinearity between variables. All analyses were carried out in R 4.0.2 (R Core Team 2020).

Results

We collected 433 individuals of *R. diptycha* in Fernando de Noronha between 2008 and 2019. In 2008 we recorded a prevalence of 58.8% (n = 33), in 2009 40.2% (n = 127), in

Table 1. Sample sizes and anomaly prevalence for each *Rhinella diptycha* age and sex categories studied in the archipelago of Fernando de Noronha between 2014 and 2015.

	Number of individuals	Number deformed	Deformity prevalence	Eye deformity prevalence
Adult males	273	124	45.4%	46 / 16.8%
Adult females	106	36	34.0%	13 / 12.3%
Juveniles	54	11	20.4%	3 / 5.6%

2014 43.5% (n = 51), in 2015 51.6% (n = 33), and in 2019 61.4% (n = 70) of anomalies. We detected a combined anomaly prevalence (for all of the period 2008 to 2019) of 42.2% for adult and 20.4% for juvenile individuals. Eye deformity frequency in adults and juveniles reached 15.6 and 5.6%, respectively, for the study period (Table 1). The most common anomaly was brachydactyly on forelimbs, accounting for almost 28% of the sampled population, followed by brachydactyly on hindlimbs (12%), anophthalmia, and ectrodactyly in hindlimbs, with both of the latter accounting for 5%

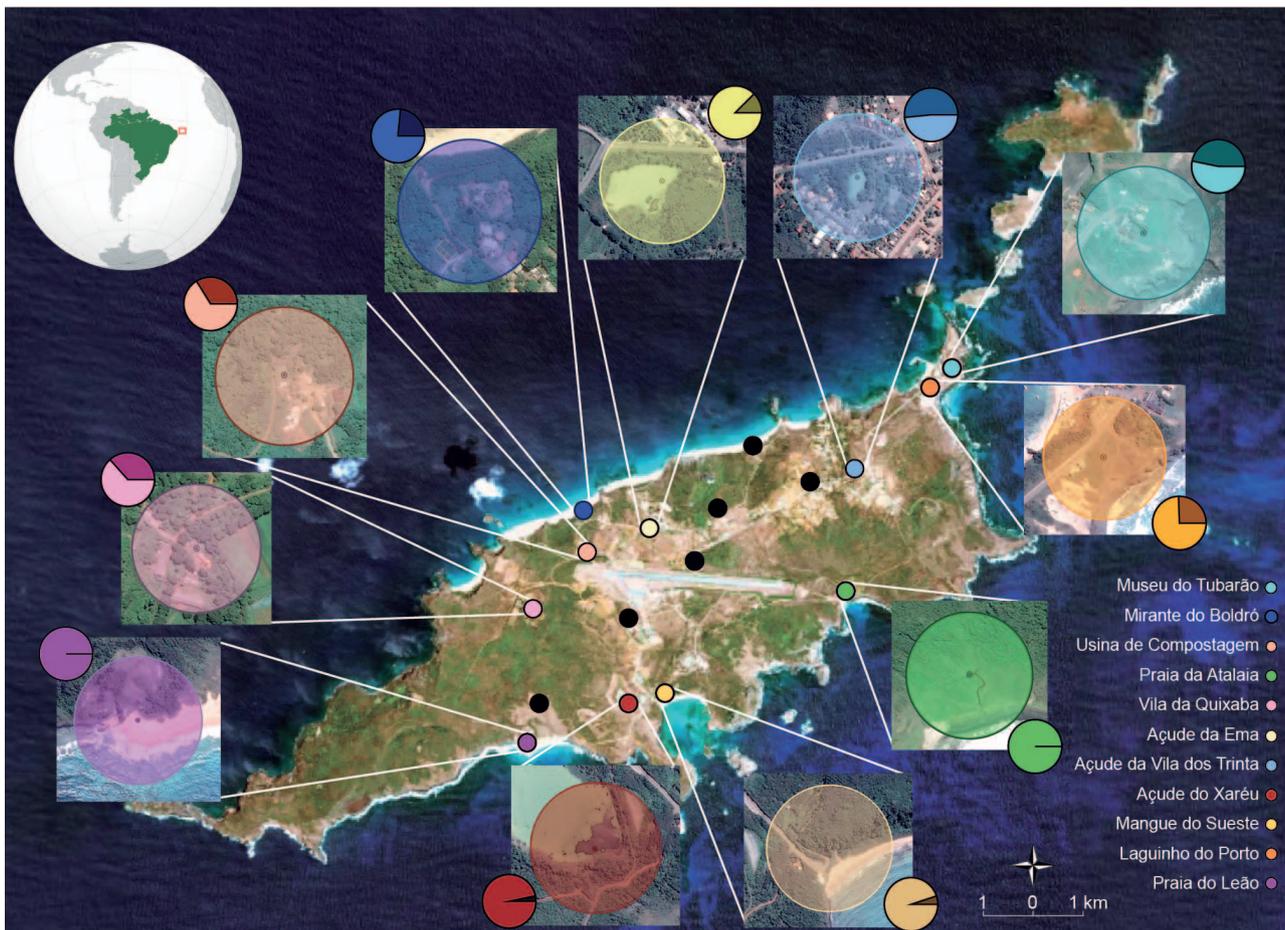


Figure 1. Sampling sites of *Rhinella diptycha* on the Archipelago of Fernando de Noronha including 300-m perimeter zones, and pie charts with percentages of anthropogenic habitat disturbance represented by darker colours and natural vegetation by lighter colours. Only two surrounding zones had no anthropogenic habitat disturbance (Praia do Leão and Praia da Atalaia).

Table 2. Types of deformities recorded in the population of *Rhinella diptycha* in Fernando de Noronha. Values based on previous studies (TOLEDO & RIBEIRO 2009; COBO-CUAN et al. 2020) and values in parentheses are those incorporated into the present study. Terminology follows HENLE et al. (2017c). Values in bold refer to novel deformity categories.

Type of deformity	Description	Juvenile	Adult
Cephalic			
Microcephaly	Head small, nose blunt; shortened upper jaw	0	1
Mandibular hypoplasia	Lower jaw abnormally short	0	1
Tympanum deformed	Tympanum irregularly shaped	0	4
Nostril skin absence		0	1
Parotoid gland reduced		0	1
Brachycephaly	Head shorter than normal	0	2
Eyes			
Eye discoloration	Iris pigment discolored or absent	0	3
Eye perforated		0	1
Anophthalmia	Eye missing	1	12 (8)
Eyelid fused to the skin		0	5
Eyelid absent		0	1 (2)
Nictitant membrane deformed		0	1
Cataract		0	5
Dilated pupil		0	1
Microphthalmia	Small eye	2	3
Concave Iris		0	1
Axial			
Deformed urostyle	Urostyle incorrectly inserted	0	1
Lateral marginal osteophytes in urostyle	Proximal portion of urostyle with a lateral salient part	0	1
Leucism	Body pigments lacking, eye colour normal	1	1
Open wound on dorsum		0	5
Forelimbs			
Brachydactyly	Abnormal number of phalanges and normal metatarsal	3	6 (20)
Ectrodactyly	Digit missing	3	1 (1)
Polydactyly	Extra digit	0	3
Ectromelia of humerus	Distal of humerus, arm segments missing	0	1
Ectromelia of radio-ulna	Distal of radio-ulna, arm segment missing	0	1 (1)
Digit rotation	Bone bent back on itself at 90° angle	0	1
Phalanges hypertrophy		0	1
Syndactyly	Fused phalanges with no articulation	0	2
Interdigital membrane enlarged		1	2
Hind limbs			
Brachydactyly	Abnormal number of phalanges and normal metatarsal	8 (2)	46 (48)
Ectrodactyly	Digit missing	3	10 (8)
Polydactyly	Extra digit	0	1 (4)
Ectromely of tibiae and fibulae	Distal to tibiae and fibulae, leg segments missing	0	4 (3)
Digit rotation	Bone bent back on itself at 90° angle	0	5
Syndactyly	Fused phalanges with no articulation	0	2 (3)
Skin webbing	Band of skin crossing a joint	1	0
Large finger tip	Finger tip expanded or longer than normal	1	2

of deformities each. We also recorded anomalies in eight novel categories for Fernando de Noronha: three cephalic, four eye-related, one in the axial portion of the body, and one in forelimbs (Table 2, Fig. 2, Supplementary Table S1).

Additionally, we examined 92 individuals of *R. marina* from Bermuda and 87 from Hawai'i. In Bermuda, 34 individuals (36%) presented at least one anomaly: four (12%) presented deformities in the eyes, 23 in forelimbs (70%),

and eight (24%) in hindlimbs (Supplementary Table S1). In Hawai'i, none of the 23 individuals sampled in 1982 presented any anomaly and only 4.7% presented at least one type of anomaly in 2015 (Fig. 3). The records indicated a mean anomaly prevalence of 51.1% for Fernando de Noronha and 28.4% for Bermuda (Fig. 3, Supplementary Table S2). The proportions of anomalous toads from Hawai'i

and mainland Brazilian sites were lower than 11% (Supplementary Table S2).

Our most parsimonious GLM included anthropogenic habitat disturbance, SVL and sex as predictors of deformities (whole model test: $\chi^2 = 51.370$; d.f. = 3; $p < 0.0001$; Table 3). In this model, anthropogenic habitat disturbance and SVL were both positive predictors of deformities and males

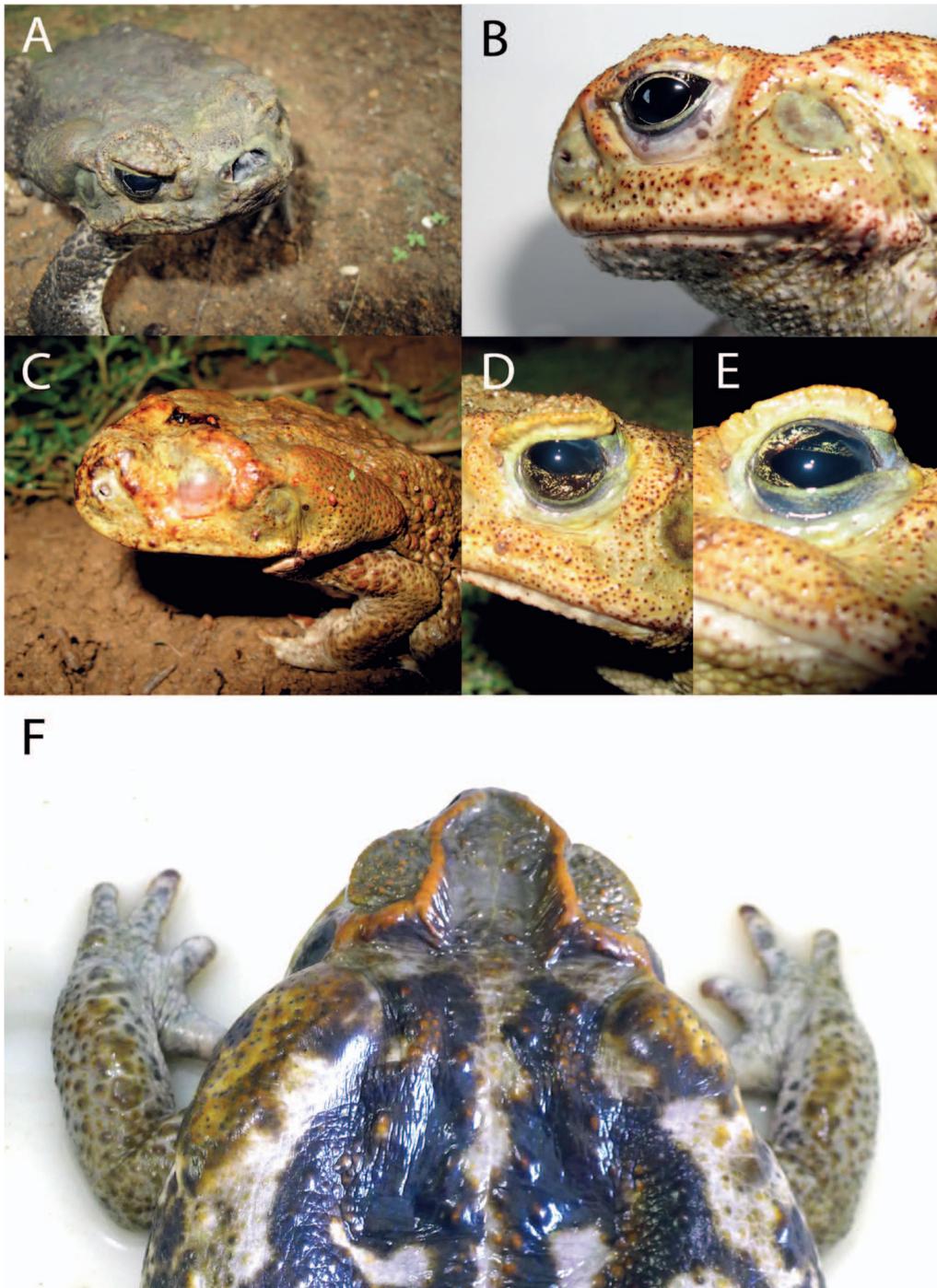


Figure 2. Examples of new types of deformities recorded in this study: nostril skin absent (A); brachycephaly (B); anophthalmia (C); concave iris (D and E); and right parotoid gland underdeveloped (F).

Table 3. Most parsimonious General Linear Model, with binomial distribution and logit link, simultaneously testing the potential effects of anthropogenic habitat disturbance, sex, and snout-vent length (SVL) on the proportion of deformities in Fernando de Noronha toads. Variance Inflationary Factor (VIF) is given for each variable and highlights no multicollinearity in the model.

Variables	b	Std Error	χ^2	VIF	p
Intercept	-5.522	1.566	13.257	-	<0.001
Anthropogenic habitat disturbance	0.027	0.006	23.885	1.032	<0.001
Sex [% males]	0.020	0.007	9.231	1.180	0.002
SVL	0.235	0.103	5.332	1.188	0.021

had a higher likelihood of carrying anomalies than females. Anthropogenic habitat change was the main explanatory variable according to our AICc model selection (Supplementary Table S3), and it was also a positive predictor of deformities when analyzed independently in a single logistic regression ($b = 0.032$, $\chi^2 = 40.308$, $p < 0.0001$; Fig. 4).

Discussion

Our analysis revealed that all considered variables (size, sex and anthropogenic habitat disturbance) have a significant influence on anomaly prevalence. The purported influence of size probably reflects the increased difficulty of detecting certain anomalies in small individuals, considering that some malformations in the limbs, especially in fingers and toes, are less obvious in juveniles than in adults. This outlines the need for more accurate methods to examine anomalies in anurans. Also, we observed a direct relationship between sex and anomalies, i.e., the more males there were in a population the higher was the prevalence of anomalies. Several hypotheses can explain this result, such as a hormonal influence on the appearance of anomalies, an influence of migration behaviour during the partitioning of reproductive niches that might expose males to other contaminant concentrations, or even a synergistic relationship of both. However, since our study is the first highlighting these aspects, we still have no evidence for any of these hypotheses.

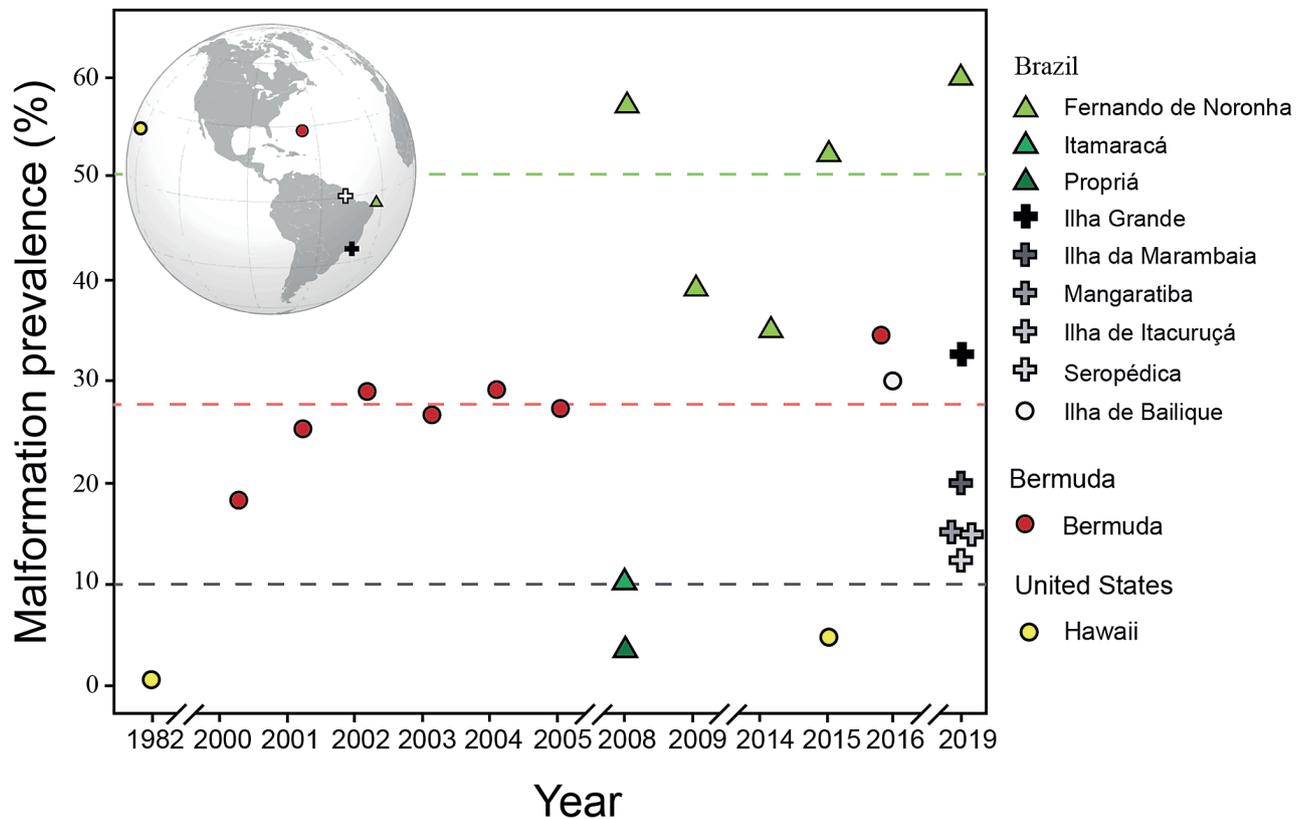


Figure 3. Deformity prevalence across sampling years. Dashed lines represent average values for Fernando de Noronha (olive) and Bermuda (red), and the grey line represents the 10-% threshold for the upper limit of naturally occurring anomalies indicated by LANNOO (2008). Data from Bermuda between 2000 and 2005 were extracted from BACON et al. (2006); and from Itamaracá, Propriá and Fernando de Noronha between 2009 and 2010 were extracted from TOLEDO & RIBEIRO (2009). Data from Ilha Grande, Ilha da Marambaia, Ilha de Itacuruçá, Seropédica and Mangaratiba, provided by REBOUÇAS et al. (2019b); and from Ilha de Bailique, provided by BESSA-SILVA et al. (2016), were inserted as the publication year (2019 and 2016, respectively) since more precise collection data are unavailable. Other data were collected in the present study. Triangle: *Rhinella diptycha*; circle: *R. marina*; cross: *R. ornata*.

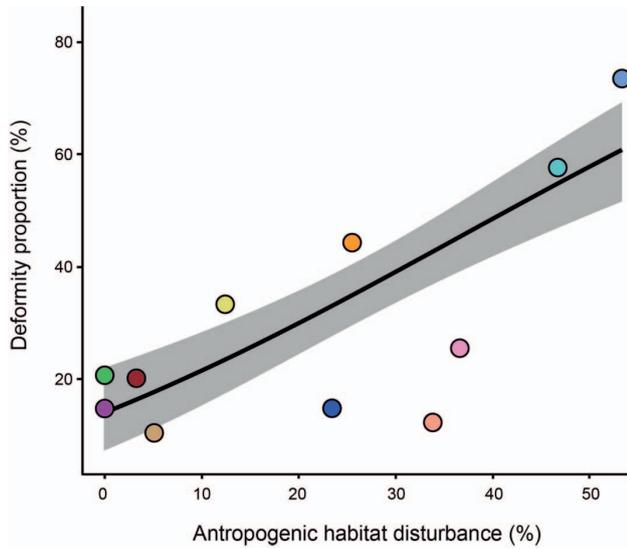


Figure 4. Logistic regression (dark line) indicating a significant association between anthropogenic habitat disturbance and proportion of deformity in toads. Colours refer to the sampling sites in Figure 1. 95-% confidence interval is highlighted in grey.

Our results underscore a correlation between human interference and deformity prevalence in the Cururu Toads from Fernando de Noronha. Anurans are highly sensitive to water pollution (DEGARADY & HALBROOK 2006, LEBBORONI et al. 2006), thus the higher prevalence of deformities in Cururu Toads sampled from disturbed habitats could be a result of environmental contamination in this archipelago. Other places, especially on the mainland, present more environmental contamination that could be reflected in anomalies in local anuran populations, however, islands are more prone to show higher prevalences of anomalies because anurans in these environments are not able to move away if the environment is contaminated as they would on the mainland. Therefore, environmental contamination associated with isolation make island sites more likely to have toads with higher anomaly prevalences. Another plausible mechanism explaining a higher commonness of deformities in disturbed habitats, which includes urban areas and roads, is the high abundance of insect prey near street lights. Easy access to prey through a sit-and-wait foraging strategy could allow blind or deformed toads to maintain their high frequency in disturbed habitats. These effects are not mutually exclusive

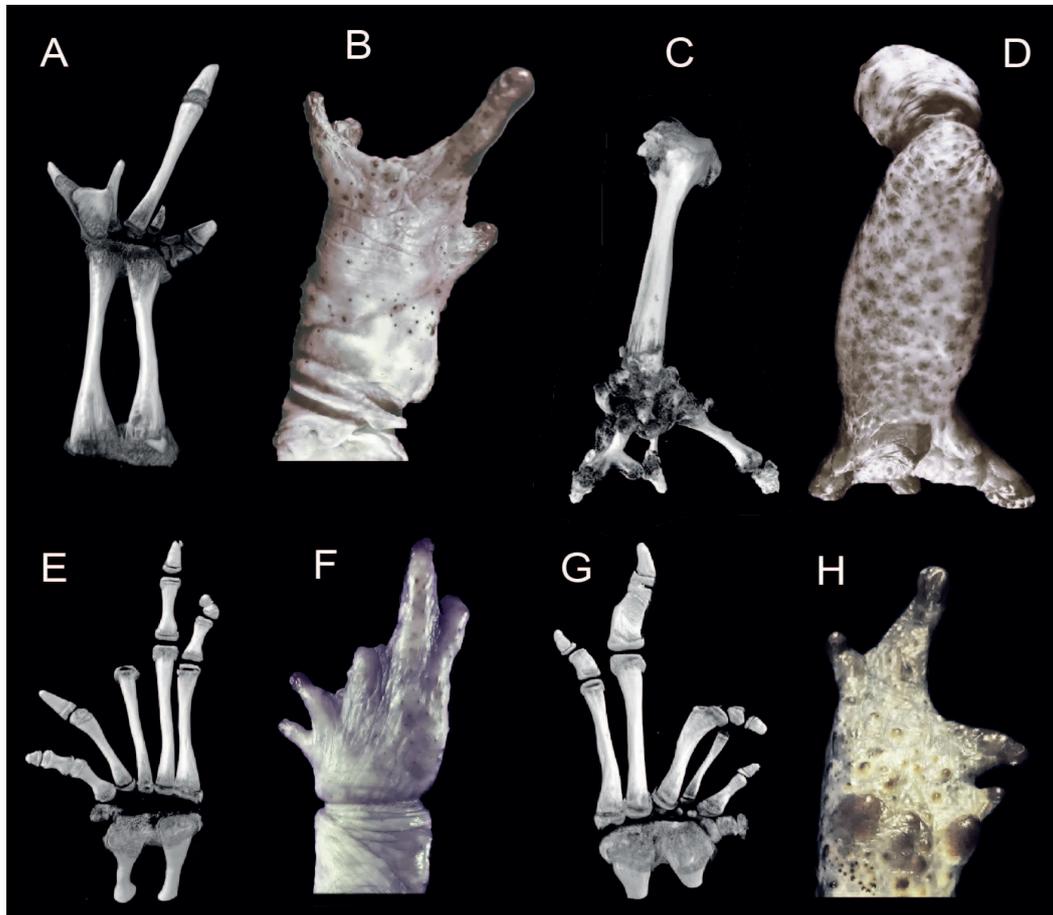


Figure 5. Comparison between tomographic (A, C, E and G) and macroscopic views of deformities (B, D, F, and H). (A–D) hindlimbs, (E–H) forelimbs.

and could in fact be acting synergistically. Similarly, the deformities in Cane Toads from Bermuda were related to environmental contaminants, particularly petroleum hydrocarbons, boosted by exposure to ultraviolet light (BACON et al. 2013). We did not record the intensity of ultraviolet exposure across the sampling ponds, but areas with presumed low UV intensity, such as shrubby areas, harboured populations with lower proportions of deformed individuals (Fig. 4).

Alternatively, the causes of anomalies could be genetic and not environmental; this population might be exposed a genetic bottleneck effect, resulting from continuous inbreeding due to a small founder population having been introduced to the archipelago about 100 years ago (FORTI et al. 2017). This bottleneck effect, combined with habitat disturbance, is another possible explanation for the high frequency of deformities in Fernando de Noronha toads. However, the high number of seemingly unrelated anoma-

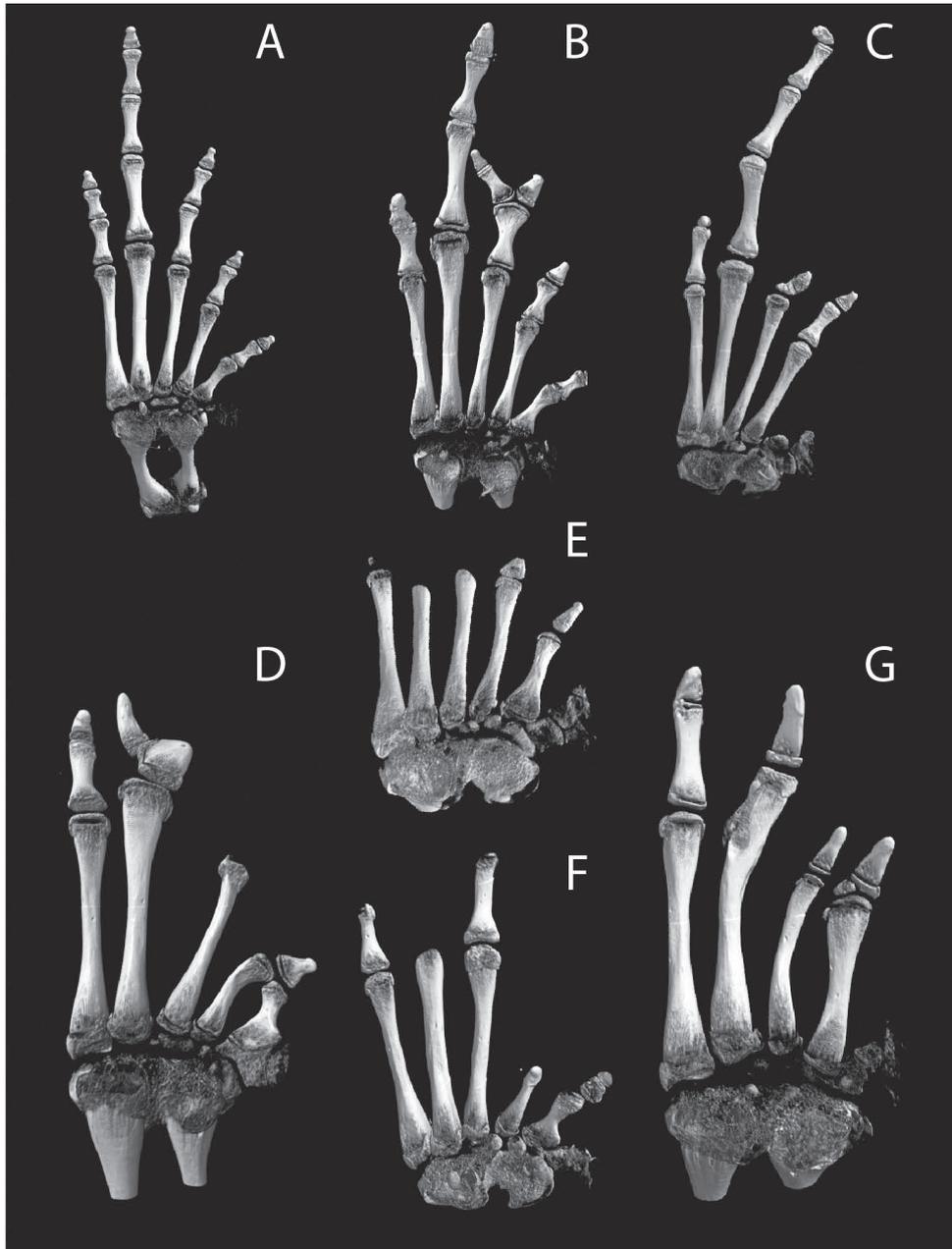


Figure 6. Examples of observed feet anomalies of *Rhinella diptycha* individuals from Fernando de Noronha: normal foot (A); post-axial polydactyly (B); brachydactyly in Fingers II, III and V and ectrodactyly in finger I (C); syndactyly in Fingers I and II, phalanges absent in Finger III, brachydactyly in Fingers IV and V, and bone rotation in finger I (D); brachydactyly in Fingers I and II, and ectrodactyly in Fingers III, IV and V (E); brachydactyly in Fingers I and II, and ectrodactyly in Fingers III, IV and V (F); and ectrodactyly in Finger I and brachydactyly in Fingers II, III, IV and V (G).

lies could indicate that inbreeding is not the leading causative mechanism, but we still lack studies to confirm this pattern. To unravel this potential mechanism, further studies could examine tissue collections from toads introduced to other islands where populations show either low frequency of anomalies (Hawai'i) or where there is overwhelming evidence for chemical contamination as a causative agent (Bermuda) (BACON et al. 2013). Hence, a genetic constraint (bottleneck effect and/or subsequent inbreeding) may be amplifying the effects of environmental contamination on the observed deformities.

We recorded eight new deformity types for Fernando de Noronha, three of them are novel to the literature (concave iris, dilated pupil, and lateral marginal osteophytes in the urostyle). However, since we applied additional techniques to evaluate deformities, such as CT-scan, and we described more precisely the deformities, it seems clear that a more accurate examination in future samples may reveal several other unreported deformities in both Fernando de Noronha toads or elsewhere. Also, internal anatomical examination (via tomography, necropsy or X-rays) can provide additional information on each external deformities, facilitate further conclusions about deformity characteris-

tics, and, in certain way, a more refined conclusion about possible causes (Figs 5 and 6). For example, we recorded only one cross-fusion of digits (syndactyly), and this is certainly not a common type of fusion. Also, we reported the first record of lateral marginal osteophytes in the urostyle (Supplementary Fig. S1), which was possible only through necropsy. Furthermore, by examining CT-scans, we were able to record, in the same individual, syndactyly, brachydactyly and ectrodactyly (Fig. 6D), and polydactyly and brachydactyly (Fig. 6B). These deformities would be difficult to classify based on external examination only, and studies applying different screening methods will enable researchers to describe even more sorts of anomalies. For example, a recent study using distortion-product otoacoustic emission (DPOE) recording equipment demonstrated that some individuals of this population are deaf (COBO-CUAN et al. 2020). However, the middle and inner ear anatomy was not evaluated and the use of CT-Scans could improve our knowledge of the consequences of impaired amphibian hearing.

Our current observations of eye abnormalities allowed us to speculate about how toads lost their eyes and became blind. Some deformities, such as the absence of eyelids or

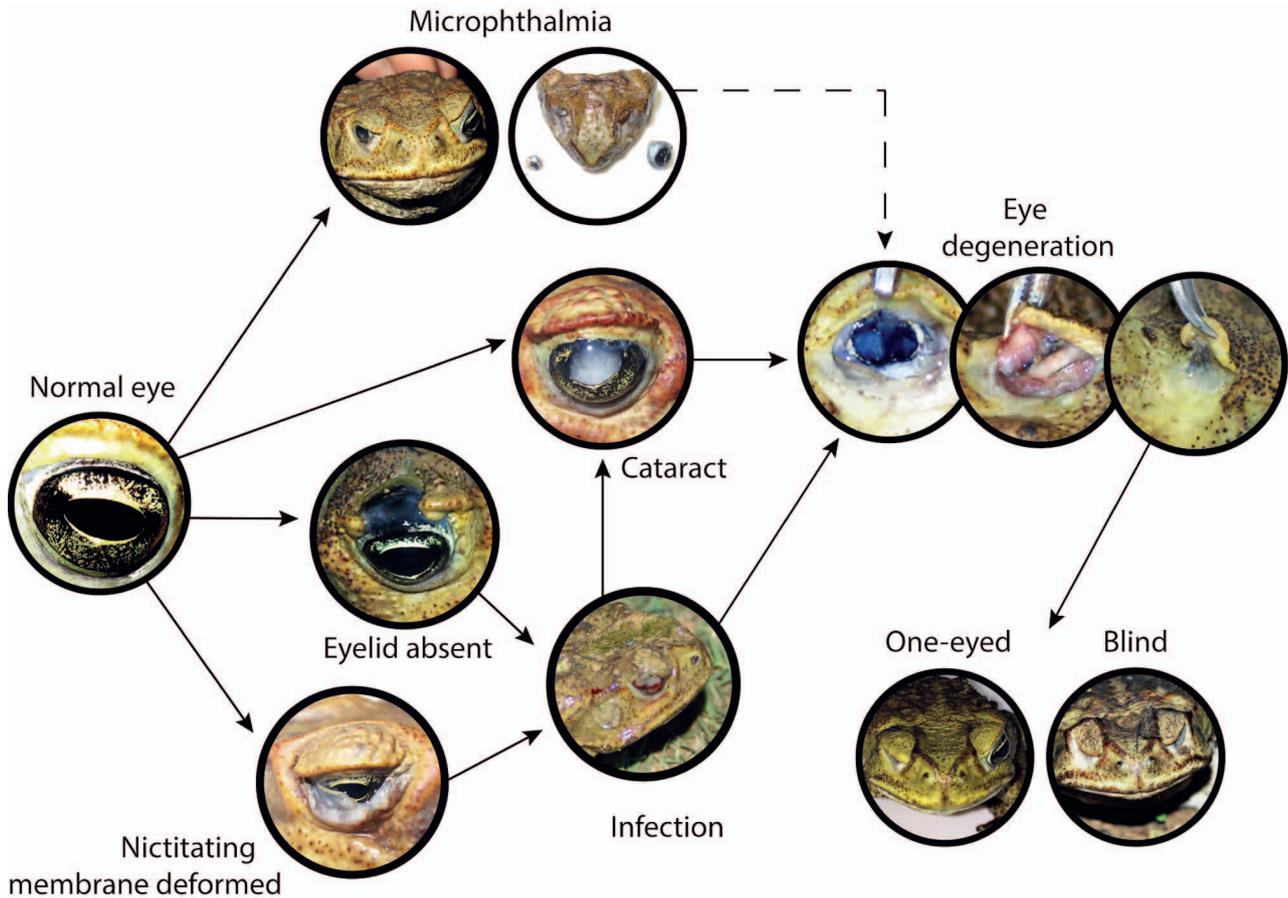


Figure 7. Flow chart linking observed eye anomalies in individuals of *Rhinella diptycha* from Fernando de Noronha, which should lead to irreversible uni- or bilateral blindness. The dashed line indicates a less plausible, but not yet recognized link, explaining eye degeneration.

deformed nictitating membranes, can promote eye infection, either due to overexposure of soft tissues to the environment or facilitating desiccation. Such infection can result directly in eye degeneration, or facilitate the occurrence of cataracts (WILLIAMS & WHITAKER 1994) and pathogenic infections (BURTON et al. 2008), which could be followed by eye degeneration, consequently resulting in irreversible uni- or bilateral blindness (Fig. 7). We are not certain if microphthalmia could be linked to eye degeneration, however it is likely that the diminished eye is not functional. The ecological consequences of uni- or bilateral blindness can be severe to individuals, impacting their feeding and reproductive fitness (TOLLEDO & TOLEDO 2015), which, in turn, could result in local population declines. However, there is no long-term population monitoring data available for the Fernando de Noronha Cururu Toad.

Our results indicate that the prevalence of anomalies observed in Fernando de Noronha slightly increased over the last decade, but the data also presented some variability over time (Fig. 3), which prevents us from drawing more precise conclusions. Thus, the causative agent of anomalies in Fernando de Noronha (or the combination of stressors) could have increased or simply oscillated during the 15-year timeframe of our study. In Bermuda, an island site with a longer historical dataset (2000–2016), the anomaly prevalence remained between 19 and 36% (BACON et al. 2006, this study). When comparing rates of deformities, the *Rhinella* spp. populations of Hawai'i and mainland Brazil (Itamaracá, Propriá, Seropédica and Mangaratiba) presented similarly low rates, close to or lower than the suggested 10% threshold (LANNOO 2008, TOLEDO & RIBEIRO 2009, REBOUÇAS et al. 2019b). This could also indicate that the causative factor present on the Bermudas and on Fernando de Noronha is absent in those other islands.

Here we demonstrated that the prevalence of anomalies might be related to human interference in the environment and that the rate of anomalies may have increased in the past decade. Further studies looking at the potential impacts of environmental pollution on Fernando de Noronha toads might shed new light on mechanisms possibly jeopardizing other vertebrates, including endemic and endangered ones, and perhaps impacting human health as well.

Acknowledgements

We thank ALLAN PESSIER and CATIA DEJUSTE DE PAULA for field samples and for providing the CT-scans; AMBER WRIGHT helped with the Hawai'i survey, TAMILIE CARVALHO helped with map-maths, and BÁRBARA REBOUÇAS is thanked for her help with diagnostics. We thank two anonymous reviewers for their helpful comments. RR thanks the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for a fellowship (process number #001), and LFT thanks the São Paulo Research Foundation (FAPESP #2016/25358-3; #2019/18335-5) and National Council for Scientific and Technological Development (CNPq #300896/2016-6; 302834/2020-6) for grants and fellowships. Collecting permits were granted by the ICMBio (SISBio#65605-2) and approved by the local animal care committee CEUA/UNICAMP (#5011-1/2018).

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Appendix

List of material examined

Rhinella diptycha (n = 23): UNITED STATES: Hawai'i: Kaneohe, BPBM 8421, BPBM 8422, BPBM 8423, BPBM 8424, BPBM 8425, BPBM 8426, BPBM 8427, BPBM 8560, BPBM 8563;

Honolulu: Lo'i Kalo, BPBM 9934, BPBM 9935, BPBM 9936, BPBM 9937, BPBM 9938, BPBM 9939, BPBM 9940, BPBM 9941, BPBM 9942, BPBM 9953, BPBM 9954, BPBM 9955, BPBM 9957, BPBM 9958.

Supplementary data

The following data are available online:

Supplementary Figure S1. Examples of abnormalities recorded in *Rhinella diptycha* from Fernando de Noronha.

Supplementary Table S1. Anomalies in toads recorded from Bermuda and Fernando de Noronha, including reclassifications of the types of deformity.

Supplementary Table S2. Frequency and mean prevalence (in percentage) of anomalies in post-metamorphic individuals of *Rhinella marina* (Bermuda and Hawai'i), *R. jimi*, and *R. ornata* (Brazil).

Supplementary Table S3. All possible logistic GLMs including the three explanatory variables, without their one-level interactions, on the proportion of deformities across our 11 sampling sites.