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RESEARCH ARTICLE

Water conditions influence the detectability of *Crossodactylus gaudichaudii* (Anura, Hylodidae) in streams of the Atlantic Forest

Juliane Pereira-Ribeiro[1] | Thais Linause[2] | Átilla C. Ferreguetti[1] | Jonathan Cozer[2] | Helena G. Bergallo[1] | Carlos Frederico D. Rocha[1]

[1]Department of Ecology, Rio de Janeiro State University, Rio de Janeiro, Brazil

[2]Department of Biology, Federal University of Espírito Santo, Vitória, Brazil

Correspondence
Juliane Pereira-Ribeiro, Department of Ecology, Rio de Janeiro State University, Rio de Janeiro, Brazil.
Email: julianeribeiro25@gmail.com

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Abstract
Stream-dwelling amphibians' occurrence, behaviour and reproductive success are strongly influenced by dynamic abiotic factors, for example, water flow and spray. These factors can disproportionately affect these frogs due to their dependency on specific favourable conditions for development and incapacity to disperse from unfavourable environments. We analysed the influence of environmental covariates on the detectability of *Crossodactylus gaudichaudii*, an amphibian species endemic to streams in the Brazilian Atlantic Forest. We conducted sampling in the streams of the Duas Bocas Biological Reserve, Brazil, and we measured air and water temperature, air humidity and pH of water on each sampling occasion. We estimated the effects of variables on the detectability of the species using single-season occupancy models. Our results indicated that the detectability of the species increases on occasions with higher water temperatures (24–26°C) and lower pH (5.0–5.5). We investigated the influence of these covariates only on the detectability of adult frogs, but it is likely that the physiochemical properties of stream water are more important to aquatic larvae, and hence, the probability of their detection. Given this, further studies should examine the relevance of covariates on the detectability of adult frogs as well as larvae.

KEYWORDS
amphibians, detection, frogs, modelling occupancy, pH, temperature

INTRODUCTION

Stream-dwelling amphibians are closely tied to water flow and spray throughout their life cycle, making them vulnerable to changes in aquatic environments (Almeida-Gomes et al., 2014; Kupferberg et al., 2012). Consequently, the physical conditions of the environment and water parameters such as light intensity, pH, conductivity, temperature and turbidity are important for amphibians in riparian locations since they can influence species' abundance and reproductive activity (e.g., Almeida-Gomes et al., 2014; Hatano et al., 2002; Motta-Tavares et al., 2019). Therefore, the detectability of amphibians in streams is expected to vary according to habitat conditions (Asad et al., 2020).

The estimation of the detection probabilities, as well as the evaluation of factors that influence the detectability of a species, is an important tool that contributes to the planning of effective and low-cost monitoring in the long term (MacKenzie et al., 2002). Here, we analysed the influence of some aspects of air and water conditions as environmental covariates to detection on the detectability of *Crossodactylus gaudichaudii* in an Atlantic Forest area, in Brazil. *Crossodactylus gaudichaudii* is a small amphibian species of the Hylodidae family, which strictly inhabits rocky streams within the Atlantic Forest (Izecksohn & Carvalho-e-Silva, 2001; Weygoldt & Carvalho-e-Silva, 1992). Crossodactylus gaudichaudii is currently classified as 'Least Concern' by the International Union for Conservation of Nature (IUCN) in terms of its conservation status. However, this species is susceptible to potential threats arising from habitat degradation, pollution, and various environmental stressors (Rocha & Van Sluys, 2004). This species exhibits activity throughout the year, which can be influenced by air temperature, relative humidity and light intensity (Almeida-Gomes, Van Sluys, & Duarte Rocha, 2007; Weygoldt & Carvalho-e-Silva, 1992). The vocalization behaviour of male frogs is primarily regulated by photoperiod, indicating a correlation between daylight hours and their calling activity (Almeida-Gomes, Van Sluys, & Duarte Rocha, 2007). This species tends to utilize the habitat horizontally, occupying various microhabitats and often being found partially immersed in water (Almeida-Gomes, Van Sluys, & Duarte Rocha, 2007; Izecksohn & Carvalho-e-Silva, 2001). Its diet consists exclusively of arthropods, with food items including insect larvae, beetles and ants (Almeida-Gomes, Hatano, et al., 2007). Given that this species is predominantly found partially immersed in water, we hypothesized that water variables would be the primary determinant of its detectability, despite some observations of the species on rocks and damp soil along stream banks (Almeida-Gomes, Hatano, et al., 2007).

METHODS

Study site

Duas Bocas Biological Reserve (DBBR) is located in the municipality of Cariacica (20°14′04″ and 20°18′30″ S; 40°28′01″ and 40°32′07″ W), in the state of Espírito Santo, southeastern Brazil. The DBBR plays an important role in the conservation of the biodiversity of the state of Espírito Santo, integrating one of the priority ecological corridors for state conservation, as well as being of fundamental importance for the water supply to the population of the municipality of Cariacica (José et al., 2016; Tonini et al., 2010).

DBBR is part of the Duas Bocas River Basin, which has an area of 92.27 km^2 (9226.88 ha), with about 30% located in DBBR. The DBBR has a total area of 2910 ha, with an elevation range between 300 and 738 m, with about 80% covered by native ombrophilous forest and the remaining 20% distributed among secondary forests, dams, streams and riparian zones (Tonini et al., 2010). The climate in the area is a humid tropical climate, with monthly average temperatures ranging from 19°C in the winter to 25.5°C in the summer, with an average annual rainfall of approximately 1500 mm and mean relative air humidity above 70% (Tonini et al., 2010). The dominant vegetation in the region is dense ombrophilous forests.

Data collection

We sampled from February 2018 to March 2019, with monthly campaigns from two up to four days, using active search methods, with visual and auditory sampling. We sampled during the day (08:00–17:00) and night periods (18:00–23:00). We distributed 22 standardized transects across different streams in the reserve (Figure 1). Transects were 50 m long, stream

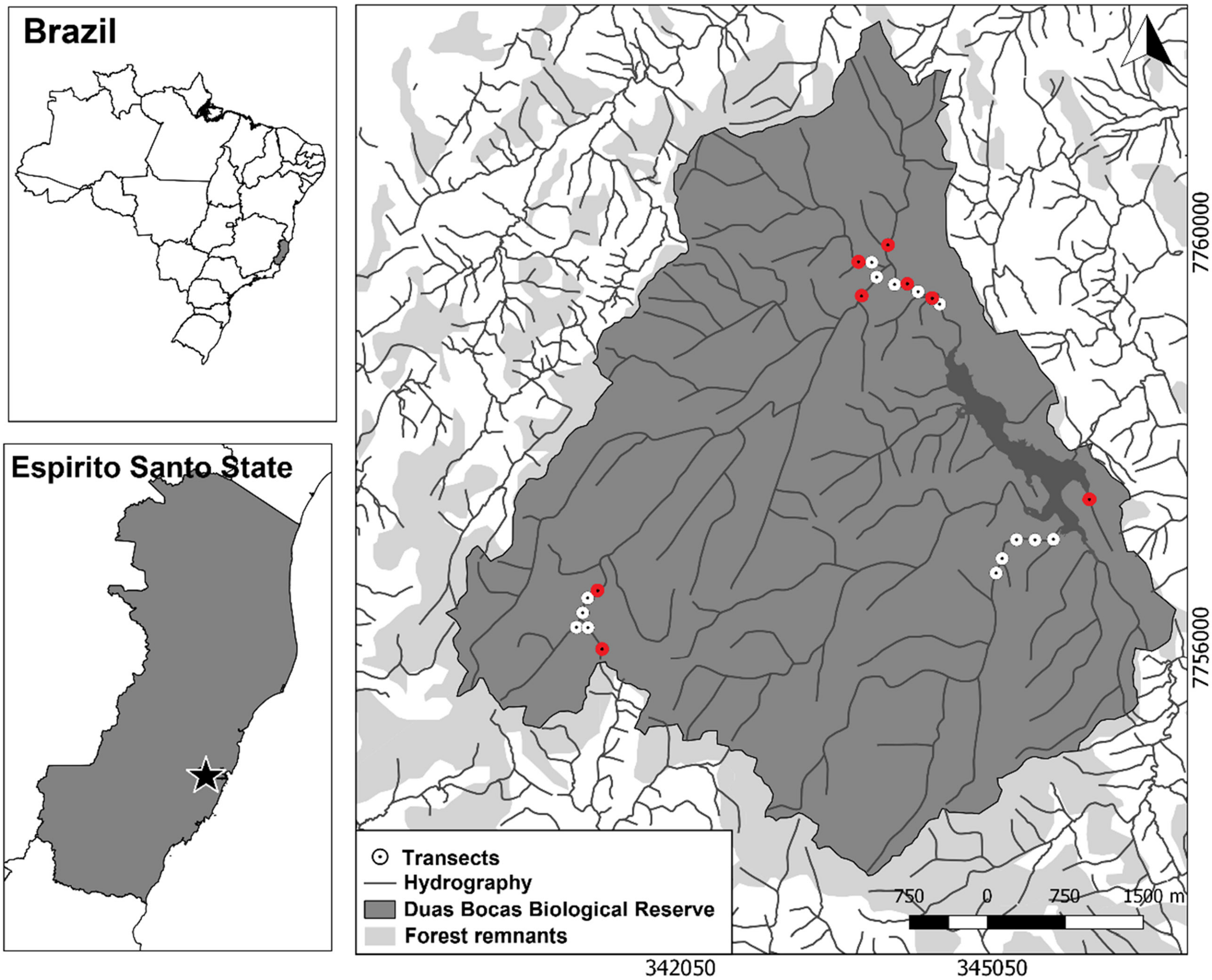

FIGURE 1 Location of the Duas Bocas Biological Reserve, municipality of Cariacica, southeastern Brazil, showing the location of the transects (circles). White circles = occupied transects (at least one detection), red circles = unoccupied transects (no detections).

centered and the width extended 2 m beyond both banks. Transects were separated by a distance of at least 50 m.

We sampled 16 transects four times, twice in the daytime and twice in the night and six transects were sampled three times, twice in the daytime and once in the night, due to the difficulty in logistics for access to areas nightly. In each transect, sampling was performed over 50 min. Before each transect, we measured the air temperature (°C) and relative humidity (%) using a thermohygrometer. In addition, we measured stream water temperature (°C), and pH, using a Multi-Parameter (®Simokit pH /EC-983). Transect surveys were conducted by at least two personnel actively searching for frogs in the water, among low vegetation and on the ground; including under rocks, leaf litter, vegetation, in rock crevices, among tree roots and trunks and along stream banks. We recorded all individuals observed or detected visually or aurally. We did not sample the same transect more than once a day. Samplings in each transect were spaced at least 1 month apart.

Data analysis

To estimate detection probabilities, we used single-season occupancy models in the PRESENCE software (MacKenzie et al., 2002). This model assumes that sites have been closed to changes in occupancy between the first and last visits of a given sampling station. Detection covariates included air temperature (°C), relative humidity (%), water temperature (°C) and pH. We modelled detection probability as a function of the covariates measured in each sampling, assuming that all sites were occupied and keeping the occupancy constant (i.e., Ψ [.]p[covariates]; MacKenzie et al., 2002). We tested the correlation between the measured variables and those with a correlation coefficient (r) > 0.60 were discarded to avoid collinearity of variables. We selected the most consistent models in terms of explanation using the Akaike Information Criterion (AIC) adjusted for a small sample size (AICc). All models with ΔAICc value <2 was considered to have a high level of support. We used 2000 bootstraps to evaluate the fit (z) and the overdispersion parameter ($\hat{c}$).

RESULTS

We recorded 70 individuals of *C. gaudichaudii* and detected the species in 14 of the 22 transects distributed over the area. The estimated detectability probability was 52% (0.52 ± 0.07).

Air temperature and water temperature covariates had a high-correlation coefficient (>60%), and we chose to include only the water temperature in the models. The most adjusted detectability models contained the variables of pH and water temperature (Table 1). The detectability of *C. gaudichaudii* had a negative relationship with pH, with higher detection probabilities occurring in occasions with lower pH (Figure 2a). On the other hand, the water temperature had a positive relationship with the detectability of the species, showing greater detection on occasions with higher water temperature (Figure 2b). The probability of detecting the species was highest between 24°C and 26°C and pH between 5 and 5.5.

The average water temperature considering all transects was 22°C (18.5°C–24.6°C), and the average pH was 6.42 (5.2–6.9). Table 2 shows the averages of the variables for occupied/unoccupied sites and surveys with detection/non-detection.

DISCUSSION

Our results showed that the detectability of *C. gaudichaudii* was influenced by water temperature and pH. Water temperature influences the survival

TABLE 1 Detectability models for the *Crossodactylus gaudichaudii* in the Duas Bocas Biological Reserve, Brazil.

Model	AICc	ΔAICc	AICcw	*K*
Ψ (.), p (pH)	102.98	0.00	0.49	3
Ψ (.), p (pH, Wt)	104.13	1.15	0.28	4
Ψ (.), p (pH, humid)	105.48	2.50	0.14	4
Ψ (.), p (pH, Wt, humid)	107.44	4.46	0.05	5
Ψ (.), p (.)	109.18	6.20	0.02	2
Ψ (.), p (Wt)	111.03	8.05	0.01	3
Ψ (.), p (humid)	111.46	8.48	0.01	3
Ψ (.), p (Wt, humid)	113.91	10.93	0.00	4

Note: Covariates: pH of the occasion (‘pH’), water temperature of the occasion (‘Wt’), and relative humidity accumulated of the occasion (‘humid’).

AICcw, akaike weight; *K*, number of parameters; p, detectability; Ψ, occupancy.

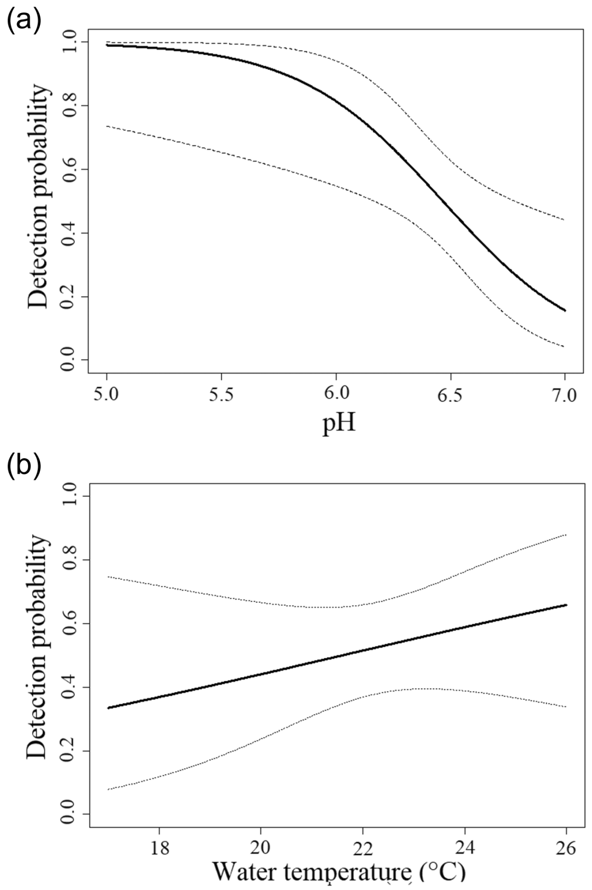

FIGURE 2 Relationship between the probability of detection of *Crossodactylus gaudichaudii* with pH (a) and water temperature (b) in Duas Bocas Biological Reserve, Cariacica, Brazil. Dashed lines indicate 95% confidence intervals.

TABLE 2 Values of water temperature and pH covariates between occupied/unoccupied sites and surveys with detections/non-detections of *Crossodactylus gaudichaudii* in streams in the Atlantic Forest, Brazil.

Variable	*N*	Average/Range
Water temperature (°C)		
Occupied transects (at least one detection)	14	22.19 (19.1–24.6)
Unoccupied transects	8	21.80 (18.5–24.6)
Surveys that resulted in detections	31	22.35 (19.7–24.6)
Surveys that resulted in non-detections	51	21.83 (18.5–24.6)
pH		
Occupied transects (at least one detection)	14	6.41 (5.2–6.9)
Unoccupied transects	8	6.43 (5.45–6.9)
Surveys that resulted in detections	31	6.31 (5.2–6.9)
Surveys that resulted in non-detections	51	6.47 (5.45–6.9)

of amphibians through mediating the development and growth of juveniles (Fatorelli & Rocha, 2008; Hochachka & Somero, 1984; Moore, 1939). In addition, temperature can influence frog species that lay their eggs in aquatic environments where large temperature fluctuations can occur throughout the day, such as ephemeral ponds and streams (Haddad & Prado, 2005). This is the case for *C. gaudichaudii*, which is a species that has higher diurnal activity and lays eggs in underwater chambers, and tadpoles remain in streams after the eggs hatch (Haddad & Prado, 2005). Water temperature is a known factor that can influence the detectability of amphibians across different life stages, with both positive and negative effects depending on the species and study location (e.g., Cook et al., 2011; Moreira et al., 2015). For example, the detectability of seven frog species in the United States was positively influenced by water temperature, indicating that frogs were more likely to call on warmer nights (Cook et al., 2011). In Brazil, the detectability of tadpoles of two species (*Dendropsophus minutus* and *Scinax squalirostris*) was positively associated with water temperature, while the detectability of *Boana pulchella* was negatively associated with the same factor (Moreira et al., 2015). We observed a positive correlation between water temperature and the detection rate of *C. gaudichaudii*. Almeida-Gomes, Van Sluys, and Duarte Rocha (2007), in a study in the Atlantic Forest, showed that the calling activity of *C. gaudichaudii* is predominantly diurnal and influenced by air temperature. In the present study, the air and water temperature variables were correlated. Therefore, the species' higher detectability at higher water temperatures is possibly due to intensified calling activity during the hottest periods of the day.

Changes in water chemistry can affect the breeding behaviour of stream-dwelling frogs (Gascon & Planas, 1986). Our results demonstrated that pH and water temperature have a significant role in the detectability of *C. gaudichaudii*. The ability of amphibians to tolerate acidic environments is influenced by several factors, such as ecology and genetics (Pierce, 1985). Although some amphibians are relatively tolerant and able to survive in acidic environments, studies have demonstrated that low pH can lead to increased mortality among species that are sensitive to acidic water, resulting in decreased hatching success and negatively affecting amphibian growth and development (Gosner & Black, 1957; Pierce, 1985). As a result, some species of amphibians can be more abundant in aquatic environments with a more alkaline or neutral, pH (Tenzin & Dhendup, 2017). We observed a negative relationship between the detectability of *C. gaudichaudii* and pH, with a higher probability of detection at lower pH levels. This suggests that *C. gaudichaudii* may have a preference for streams with more acidic water pH, possibly being more abundant in these environments and thus more frequently detected. In fact, pH averages for occupied sites and surveys with detections tended to be slightly lower than those for unoccupied transects and surveys without detection. However, our data of stream pH averages suggested that *C. gaudichaudii* could tolerate a relatively wide pH range, occupying transects with pH levels between 5.2 and 6.9. Although our study provides new insight into the effect of pH on the detectability of this species, more experimental data and research is needed to confirm its pH tolerance and to determine whether reproduction or other aspects of the biology of this species are linked to acidic environments, increasing its detectability. It is important to highlight that, although some studies have demonstrated the importance of the pH of aquatic environments for the distribution and reproduction of amphibians (Gascon & Planas, 1986; Pierce, 1985), knowledge about the role that pH plays in the abundance and detectability of amphibians in natural environments is still quite limited (Barth & Wilson, 2010).

We conclude that water temperature and pH influence the detectability of *C. gaudichaudii* in the Atlantic Forest. Our study focused on the effects of these covariates on the detection of adult individuals of *C. gaudichaudii* but it is important to note that the effects of changing water conditions may be even more pronounced during the larval stages of amphibians (Pierce, 1985). Therefore, further research is needed to explore the effects of water chemistry on all the life stages of *C. gaudichaudii* and other amphibians inhabiting the Atlantic Forest streams.

AUTHOR CONTRIBUTIONS

Juliane Pereira Ribeiro: Conceptualization (equal); data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (equal); project administration (lead); resources (equal); supervision (lead); writing – original draft (lead); writing – review and editing (equal). **Thais Linause:** Conceptualization (equal); data curation (equal); formal analysis (supporting); investigation (equal); methodology (equal); project administration (supporting); writing – review and editing (equal). **Átilla C. Ferreguetti:** Conceptualization (equal); data curation (supporting); formal analysis (supporting); investigation (equal); methodology (equal); writing – review and editing (equal). **Jonathan Cozer:** Conceptualization (equal); data curation (supporting); investigation (equal); methodology (equal); writing – review and editing (equal). **Helena G. Bergallo:** Conceptualization (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Carlos Frederico D. Rocha:** Conceptualization (equal); funding acquisition (lead); investigation (equal); methodology (equal); project administration (supporting); resources (equal); supervision (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

All the authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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ORCID

Juliane Pereira-Ribeiro https://orcid.org/0000-0002-0762-337X
Átilla C. Ferreguetti https://orcid.org/0000-0002-5139-8835

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