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Short Communication

Distribution and invasion progress of *Eleutherodactylus coqui* (Anura: Eleutherodactylidae) introduced in Costa Rica

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The Puerto Rican Coqui, *Eleutherodactylus coqui* Thomas, 1966, is widespread and abundant in Puerto Rico (Woolbright *et al.* 2006), where the frog's constant nocturnal vocalizations make it an iconic and beloved representative species (Beard and Pitt 2012). However, outside its native range, *E. coqui* is often less appreciated and even considered a pest.

Eleutherodactylus coqui is considered among the 100 worst invasive species in the world (Lowe *et al.* 2004), particularly because of its invasion of the Hawaiian Archipelago (Kalnicky *et al.* 2014). In Hawaii the population can reach extremely high densities of up to 91,000 frogs per hectare, and it has been associated with social, environmental, and economic problems (Beard *et al.* 2009). Among those problems are the introduction of infectious agents (Beard and O'Neill 2005), alteration in the nutrient cycle (Sin *et al.* 2008), changes in the invertebrate community (Choi and Beard 2012), economic losses (Kaiser and Burnett 2006), and annoyances related to the noise of their constant vocalizations (Kalnicky *et al.* 2014).

Despite its history as invasive species, *Eleutherodactylus coqui* has received little attention since its introduction to Costa Rica nearly 20 years ago. Six individuals of *E. coqui* were intentionally released in the garden of a private residence in the city of Turrialba, Cartago

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Province, around 1998 (Barrantes-Madrigal 2017). However, it was not until 2010 that the introduction was reported in a scientific journal, noting a population of approximately 100 individuals in a residential area of the city of Turrialba, Cartago (García-Rodríguez *et al.* 2010). Since then, no research has been published about the status of their populations or the impact of the species in the country.

Lacking this basic information, it is difficult for the environmental authorities and researchers to determine what should be done about the introduced *Eleutherodactylus coqui* and to explore possible control strategies (Simberloff 2003). Currently, there is no plan to manage *E. coqui* in Costa Rica, and it seems likely that the more delayed the response from the authorities, the more the problem may escalate. As a species advances in its invasion process, it is more likely to cause negative impacts (Rejmánek and Pitcairn 2002); in addition, the cost for its management increases and the probability of success of control strategies is lowered (Simberloff *et al.* 2013). Even in the absence of any known impacts related to the presence of *E. coqui,* it is important to monitor the status of its population and the progress of its invasion (Kraus and Duffy 2010, Simberloff *et al.* 2013). Herein, we identify new areas in Costa Rica where *E. coqui* occurs to inform researchers and environmental management authorities.

Eleutherodactylus coqui is known to occur in the city of Turrialba, Canton Turrialba, Cartago Province, Costa Rica (Figure 1). The elevation of Turrialba is 600–650 m a.s.l. where the city enjoys a warm, humid climate with an average annual temperature of 22°C. Because Turrialba is located on the Caribbean slopes, it is exposed to humid winds from the northeast, and in certain regions of the district, it can receive up to 7000 mm of rain (Dufour 1978).

Land use in the city of Turrialba is mainly urban, although coffee and sugar cane are common crops in the area and represent a large percentage of the regional land cover (Instituto Tecnológico de Costa Rica 2008). Protected areas surround Turrialba, among which the closest ones are: the Guayabo National Monument, La Marta Wildlife Refuge, Barbilla National Park, Turrialba Volcano National Park, Tapantí-Macizo Cerro de la Muerte National Park, Río Macho Forest Reserve, Pacuare River Forest Reserve, Tuis River Basin Protected Area, and El Copal Biological Reserve.

In October 2016, we verified the presence of the only known population of *Eleutherodactylus coqui* in Turrialba; this was reported by (García-Rodriguez *et al.* 2010). We found a well-established population of *E. coqui* throughout an area of at least 500-m radius around the point of introduction. The site is surrounded by an area of heterogeneous composition with residential areas, open areas, paddocks, plantations, small streams, and patches of secondary forest. Based on our observations and the number of vocalizations, it seems that the population may have doubled in size since the estimates of García Rodríguez (2010). However, a more thorough analysis of the population dynamics is needed to predict future fluctuations in population size.

To identify other possible localities in which *E. coqui* might occur, we surveyed people from 67 different residential houses distributed within a 500-m radius from the point at which the species was first reported (09°53.989 N, 83°40.337 W; García-Rodríguez *et al.* 2010). The survey consisted of a questionnaire designed to determine if the respondent recognized the species, followed by a query about other places where this species could be present (Appendix I).

To broaden the scope of the survey, we posted a video with the photo and the sound of *E. coqui* on the social networking service Facebook, Inc. and requested reports of about places where the frog had been seen or heard. Two of the profiles selected for the online survey were related to the study area ("TurrialbaDigital" and "Turrialba Inteligente," with 9960 and 9104 followers, respectively), in addition to a webpage about Costa Rican herpetology ("Herpetólogos de Costa Rica", a group with 1775 members).

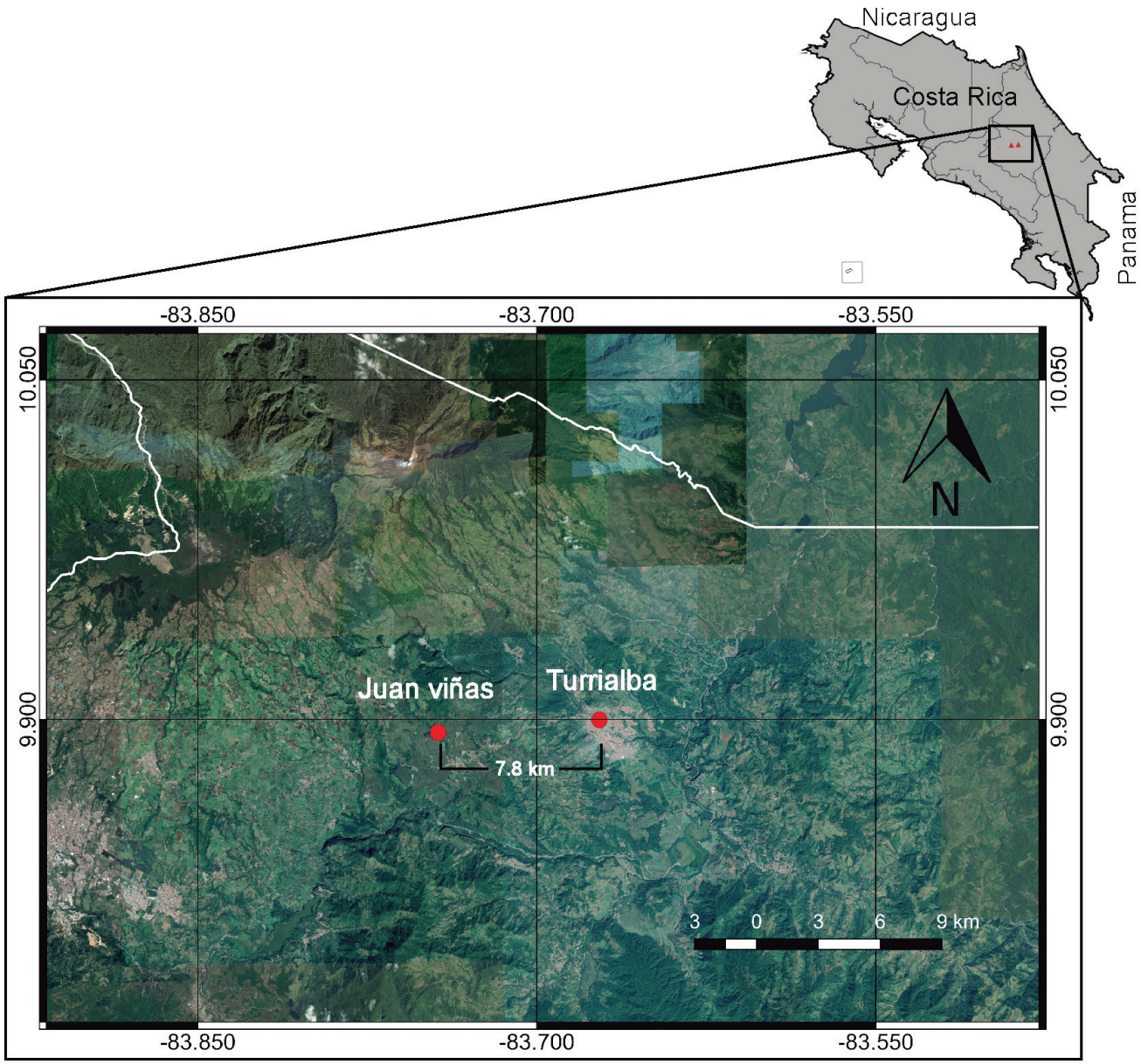

Figure 1. Established populations of *Eleutherodactylus coqui* in Costa Rica, 2019.

Five sites were reported that may harbor *Eleutherodactylus coqui*: the Invu neighborhood in Juan Viñas; the neighborhoods of El Botecito, San Juan Sur, and La Margot in Turrialba; and the Wildlife Refuge La Marta in Pejibaye, Cartago. We surveyed these sites by visual- and auditory-encounter surveys one night (20:00–22:00 h); however, we only confirmed the presence of *E. coqui* in the Invu neighborhood of Juan Viñas, a village located 7.8 km away from the introduction site of this species (Figure 1). Based on the number of vocalizations heard in this neighborhood, we estimate that there is a population of at least 60 individuals (JB, personal estimation).

This record is a new locality for *E. coqui* and one that establishes that the range of the species is expanding. Doubtless, the frog was transported by human activity, given the distance from the initial population in Turrialba and the fact that

there is no record of other population between these sites. In Hawaii, human transport played an important role in the rapid dispersal of this species throughout the archipelago (Everman and Klawinski 2013). The high population densities of common coqui frogs in infected areas favored a frequent unintentional transfer of individuals to different places, mostly in ornamental plants, plant materials, or cars. Additionally, people who liked the sound of common coqui frogs introduced them to their properties, facilitating the spread of the species (Kraus and Campbell 2002).

The other locations where the presence of *E. coqui* was reported, but no individuals were detected, may be based on incorrect identifications by our survey respondents. Some native Terrarana (Craugastoridae, Eleutherodactylidae and Strabomantidae) occurring in the area resemble *E. coqui* in size and coloration (Savage 2002). In addition, some Dink frogs (*Diasporus* spp.), which are related with *E. coqui,* and some glass frogs such as *Hyalinobatrachium fleischmanni* (Boettger, 1893) have striking vocalizations with a high pitch (Savage 2002) that could be confused with the second note of the typical song of *E. coqui.* Although we did not find another population of *E. coqui* in the country, it is possible that they simply have not been detected in our cursory survey; thus, it is important to increase sampling efforts in suspect areas to explore the spread of this invasive frog.

Based on the available information on *Eleutherodactylus coqui* in Costa Rica, we determined the invasion stage in the framework proposed by Blackburn *et al.* (2011). In this framework, the progress of the invasion of a species is determined by criteria and barriers that the species must overcome during its transfer, introduction, establishment, and dispersion until it is classified as completely invasive. The new locality reported here places *E. coqui* in dispersion stage D2, because our data suggest that there is a self-sustaining population in the wild at a site located at a significant distance from the original point of introduction. This stage implies that efforts should be made to prevent this species from dispersing further. Transport by humans is likely to result in the establishment of new populations of this frog. This threat should concern to the environmental authorities of the country, because even a single successful introduction event in an area with favorable conditions could be sufficient for this species to spread easily over a considerably larger area (Rauschert *et al.* 2017).

The common coqui frog could also continue its invasion process without human intervention. For example, a rapid evolutionary adaptation could provide this population with characteristics that allow it to overcome the limiting barriers in its invasion process (Frankham 2005, Whitney and Gabler 2008, O'Neill *et al.* 2018). Likewise, environment changes could generate favorable conditions for the dispersal of this species (e.g., climate change, natural disasters, changes in the community of plants or animals), as exemplified by the increase in the population density of *E. coqui* in Puerto Rico following Hurricane Hugo in 1989 (Klawinski *et al.* 2014).

The succession of this species toward the final stage of invasion could cause diverse negative ecological impacts, among them competition with native species. For example, it has been shown that introduced species that perform constant vocalizations can interfere with the acoustic communication of sympatric species (Both and Grant 2012). This could be especially harmful for species such as the Dink frogs (*Diasporus* spp.), which perform constant vocalizations to attract mates. Among the other possible impacts are: (1) increases in the populations of animals that prey on *E. coqui* (e.g., spiders, snakes, small mammals), which in turn could increase the rate of predation on other native species reducing their populations (Beard and Pitt 2005, Smith *et al.* 2018, Hill *et al.* 2019); (2) the introduction of parasites or infectious agents that pose a risk to native species (Beard and O'Neill 2005, Marr *et al.* 2008); and (3) the noise produced by these frogs may disturb humans in places where there is a strong

interaction with this species (Beard *et al.* 2009, Kalnicky *et al.* 2014).

Several management strategies for *Eleutherodactylus coqui* have been deployed in Hawaii (Tuttle *et al.* 2008, Hara *et al.* 2010, Pitt *et al.* 2012). Some eradicated the species (Beachy *et al.* 2011), but most of these cannot be implemented in Costa Rica. For example, one of the most effective methods used in Hawaii was to spray citric acid over the vegetation, killing all the frogs (Pitt *et al.* 2012). Unlike Costa Rica, this is possible in Hawaii because the archipelago does not have any native amphibians. Obviously, applying this kind of measure in Costa Rica would be harmful to other native species, and the solution might be worse than the problem.

In conclusion, the common coqui frog is well established at its original point of introduction. The progress of its invasion seems to be slower than the invasion in Hawaii. However, the new population found in Juan Viñas speaks to the potential for dispersal of *Eleutherodactylus coqui* in Costa Rica and the problems that might result if the dispersal of this exotic species is not checked. We recommend that environmental authorities identify and focus on the mechanisms allowing this species to spread. Particular efforts should be made to prevent people from transporting the species from one place to another.

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Appendix I. *Survey implemented on resident people of the places where* Eleutherodactylus coqui *was introduced to identify other places with presence of this species.*

Question	**Answer**
1. Have you ever heard this sound? (reproducing vocalization of *Eleutherodactylus coqui*).	Yes – Next question No – End of the survey
2. What kind of animal produces that sound?	Correct – Next question Incorrect – proceed with question four
3. Do you know other places where the species occurs?	Yes – Where? No – End of the survey
4. Have you heard that sound somewhere else?	Yes – Where? No – End of the survey