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Published in Francis, Robert A., editor. Handbook of Global Freshwater Invasive Species. Earthscan, London, 2012.

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Eleutherodactylus coqui Thomas (Caribbean tree frog)

Karen H. Beard and William C. Pitt

History of *Eleutherodactylus coqui* Introduction

Eleutherodactylus coqui (hereafter, the coqui) is a nocturnal, terrestrial frog endemic to the island of Puerto Rico (Figure 26.1). There are 16 *Eleutherodactylus* species endemic to the island, but the coqui is the most widespread and abundant. While larger than most other frogs in Puerto Rico, the coqui is a small frog (maximum snout–vent length (SVL) for males of 50mm and for females of 63mm; Joglar, 1998), that differentiates itself from other *Eleutherodactylus* species by using the full spectrum of vertical forest habitats and by its distinctive two note mating call, which sounds like 'ko-kee' and gave the frog its common name.

The coqui has established on a number of Caribbean islands to which it is not native, including Culebra and Vieques, Puerto Rico (Rivero and Joglar, 1979), St Thomas and St Croix, Virgin Islands (MacLean, 1982) and the Dominican Republic (Joglar, 1998). The coqui was also introduced to Florida in the early 1970s (Austin and Schwartz, 1975; Wilson and Porras, 1983), but has not been reported there since 2000 (Meshaka et al, 2004).

Most of the information on the coqui as an invasive has been obtained in Hawaii, and so Hawaii is the focus of this chapter. The coqui was introduced to Hawaii in the late 1980s via infested nursery plants (Kraus et al, 1999) (Figure 26.1), and, consistent with this, it first appeared in and around nurseries. There were two separate introductions: one to the island of Hawaii (Big Island) and one to Maui (Maliko Gulch), which, at least genetically, both originated near San Juan, Puerto Rico (Velo-Antón et al, 2007; Peacock et al, 2009). The coqui experienced a severe bottleneck when it was introduced, and all measures of genetic diversity are much higher in Puerto Rico than Hawaii (Peacock et al, 2009).

Since its initial introductions, the coqui has spread to the other two main islands: Kauai and Oahu; and two smaller islands: Molokai and Lanai (Kraus and Campbell, 2002; Anonymous, 2010). Subsequent spread originated from the Big Island, while the Maui introduction remains, for the most part, genetically isolated (Peacock et al, 2009). The coqui's spread was rapid. In 1998, there were only eight populations on the Big Island and Maui (Kraus et al, 1999). By 2001, there were over 200 populations on the Big Island, 36 on Maui, 14 on Oahu and 2 on Kauai (Kraus and Campbell, 2002).

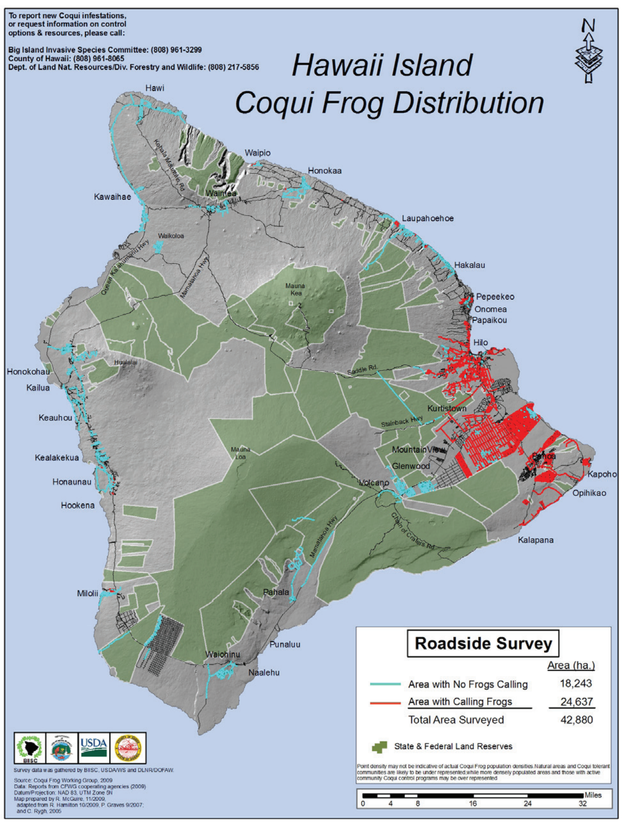
Eradication efforts have been very successful on some islands. For example, on Kauai, there is now only one population, and control efforts have kept this from spreading and reduced it to a very small area (it remains on private property where the state does not access). On Oahu, control efforts of infested nurseries, plant retailers and the one naturalized population were successful, such that Oahu has no known breeding

Source: William Pitt

Figure 26.1 Eleutherodactylus coqui *in potted nursery plant*

populations (Anonymous, 2010). While there were reports of frogs on Molokai in 2001 and 2007 and Lanai in 2002, these individuals were eradicated and these islands are no longer thought to have frogs (Anonymous, 2010).

Naturalized populations still exist on Maui and Big Island. Maui had 14 naturalized population centres but now considers seven of those eradicated, six to have very low numbers, and Maliko Gulch to be the last stronghold (Anonymous, 2010). There is a massive effort underway to eradicate the coqui in Maliko Gulch, which covers a 90ha area, and make Maui coqui free. The Big Island is a different story. On the Big Island, most of eastern part of the island is infested, and there are many established populations on the west side as well. Between 2006 and 2008, coqui occupied-areas expanded from 2800 to at least 25,000 ha (Figure 26.2). Coquis are not believed to be eradicable on the Big



Source: McGuire et al (2010)

Figure 26.2 *Distribution of* Eleutherodactylus coqui *on the Big Island*

Island, but it is thought that areas may remain coqui free (Anonymous, 2010).

At first, coquis primarily spread through the sale and movement of nursery products (Kraus, 2003). For example, both populations that became naturalized on Kauai and Oahu originated from infested shipments sent to nurseries from the Big Island. However, several sites on the Big Island were established through intentional introductions conducted by those who wanted to encourage the coqui's presence in Hawaii, show that they were too widespread to eradicate, and as a misguided insect control effort. They were intentionally introduced to state and national parks and to private properties (Kraus and Campbell, 2002; Kraus, 2003). More recently, especially on the Big Island, coquis appear primarily to be spreading from existing populations and via vehicular traffic (Peacock et al, 2009).

The coqui has spread from Hawaii to other areas. Coquis in infested plant shipments have reached both California and Guam (Campbell and Kraus, 2002; Christy et al, 2007). In California, there are confirmed reports inside nurseries and unconfirmed reports outside nurseries (Beard et al, 2009). In Guam, coquis have been captured twice outside of nurseries; in both cases, individuals were eliminated and Guam is thought to be coqui free (Beard et al, 2009).

Ecological Niche

Coquis have direct development (eggs develop into froglets, not tadpoles), and therefore do not require water bodies for any life stage. However, coquis, like all anurans, have to balance thermoregulation and hydroregulation because of their permeable skin (Preest and Pough, 1989). This is most obviously observed in changes in behaviour and activity with changes in temperature and humidity. For example, frogs move, forage, call and breed more on warm and wet nights than on cold and dry nights (Woolbright, 1985; Townsend and Stewart, 1994; Fogarty and Vilella, 2002).

The need to balance thermoregulation and hydroregulation also determines their distribution (Rogowitz et al, 1999). Coquis inhabit almost anywhere in Puerto Rico from sea level to the highest peak (1200m) as long as there is high humidity and adequate cover (Schwartz and Henderson, 1991). Their densities are highest in forested habitats, typically reaching around 20,000 frogs ha^{-1} (Stewart and Woolbright, 1996), but they also use other more marginal habitats, such as trees in urban areas and buildings (Joglar, 1998).

On the Big Island, coquis spread quickly at low elevations (<500m) of the eastern side, where mean annual precipitation is higher, but slower at high elevations (>1000m) and on the western side, where precipitation is lower (Chu and Chen, 2005). The highest elevation populations are found at 1200m, even though the highest peaks in Hawaii are around 4200m. Invasion into higher elevation forests is of concern because many endemic species are restricted to these habitats (Beard and Pitt, 2005). In Hawaii, coquis have primarily established in forests along roadsides, nurseries, residential gardens, resort areas, refuse areas and state parks.

In forests, the coqui prefers to forage and call on large leafed tree species, such as *Cecropia*, *Heliconia* and palms, which are often found near streams (Figure 26.3) (Beard et al, 2003b). They prefer these species because they support their weight for calling and foraging, and they use large fallen leaves and leaf axils for nesting and diurnal retreat sites (Townsend, 1989; Beard et al, 2003b). Nesting and retreat sites are the primary factor limiting their populations (Stewart and Pough, 1983; Woolbright, 1991,1996). Thus, areas with more vegetation structure (i.e. more nesting and retreat sites) have more frogs (Fogarty and Vilella, 2001; Beard et al, 2008).

Source: William Pitt

Figure 26.3 Eleutherodactylus coqui *on a* Heliconia *leaf*

Economic Impacts

The main public concern regarding the coqui is the noise from their calls (80–90db at 0.5m), which is greater than levels set to minimize interference with the enjoyment of life (Beard and Pitt, 2005). As a result, as people choose properties free or far from calls, property owners on the Big Island have felt the economic impacts of the invasion. If frogs are present before selling a property or home, there is a requirement to disclose this information. It has been determined that coquis cause an average of 0.16 per cent loss of real estate value per sale, which, when projected across the Big Island, is estimated to lower property values by $7.6 million (Kaiser and Burnett, 2006).

Because coquis are known to spread through the movement of plant products, the invasion has also affected Hawaii's nursery and floriculture industries, primary industries in Hawaii. In 2001, the Hawaii Department of Agriculture designated the coqui as a 'pest' and 'injurious wildlife', which makes it illegal to release, transport or export coquis. Because of this, these industries have had to pay to treat infestations (i.e. for added labour and treatment costs), they have lost time in shipping products, and they have lost products as ports of entry reject and destroy shipments (Anonymous, 2010). Nurseries with infestations have also experienced decreased sales (Beard et al, 2009). A collaborative agency certificate programme, Stop Coqui Hawaii, was initiated to educate nursery owners about protocols to reduce coquis and the public about which vendors are coqui free, but funding for the programme was discontinued (Anonymous, 2010).

County, state and federal governments also incur costs to control coquis. Costs for public agencies exceeded $4 million in 2006, but have declined in recent years. For example, the State of Hawaii Legislature spent $2 million for frog control in 2006, but only $800,000 in 2007, $400,000 in 2008, and $100,000 in 2009 (Anonymous, 2010). Current funding is not thought sufficient to keep Oahu and Kauai coqui free, eliminate frogs from Maui, and maintain levels of control on the Big Island. To do so is estimated to cost $150,000 per island each year for Oahu and Kauai; $800,000 year^{-1} for Maui; and $1.2 million year^{-1} for the Big Island (Anonymous, 2010).

Ecological Impacts

Because there are no native terrestrial amphibians or reptiles in Hawaii (Kraus, 2003), there were many concerns about the coqui's potential impacts on Hawaii's fragile native ecosystems (Kraus et al, 1999). The coqui has been described as one of the most abundant amphibians in the world, with densities approaching 50,000 ha^{-1} at times in Puerto Rico (Stewart and Woolbright, 1996). Because of this and because the coqui is a generalist insectivore, it was thought that its most likely impacts would be through predation on invertebrate numbers (Beard and Pitt, 2005).

In areas in Hawaii where coquis consistently reach densities over 90,000 frogs ha^{-1}, they are thought to consume 690,000 invertebrates ha^{-1} night^{-1} (Beard et al, 2008) and reduce invertebrate populations (Sin et al, 2008). Fortunately, coquis have been found to consume primarily non-native leaf litter invertebrates in Hawaii: ants, amphipods and isopods (Beard, 2007). However, there are groups (including Acarina, Collembola, Gastropoda, Diptera and Coleoptera) that make up a significant portion of their diets and contain native species (Beard, 2007).

Coquis also may indirectly influence the ecosystem processes that invertebrates control. For example, invertebrates play key roles in breaking down plant and leaf litter material. In Puerto Rico, herbivory rates were lower, and plant growth and leaf litter decomposition rates were higher with than without coquis (Beard et al, 2003a). Similar patterns have been found in Hawaii (Sin et al, 2008). These results suggest that coquis could increase nutrient cycling rates in Hawaii and confer a competitive advantage to non-native plants in an ecosystem where natives evolved under nutrient poor conditions (Beard and Pitt, 2005; Sin et al, 2008).

Other hypotheses regarding impacts include coquis competing with native insectivores, such as endemic birds, for prey (Kraus et al, 1999; Beard and Pitt, 2005). For example, the 'elepaio' (*Chasiempis* spp.), the 'i'iwi (*Vestiaria coccinea*) and the endangered Hawaiian hoary bat (*Lasiurus cinereus semotus*) share prey and elevations with coquis (Beard and Pitt, 2005). Kraus et al (1999) suggest that coquis may increase native bird predators, such as the black rat (*Rattus rattus*) and small Indian mongoose (*Herpestes javanicus*). although coquis have been found to be a negligible part of their diets (Beard and Pitt, 2006). Finally, coquis may serve as a food source for other potentially devastating bird predators, such as the brown tree snake (*Boiga irregularis*) or other arboreal snakes, if introduced (Beard and Pitt, 2005).

Management Approaches

Since 1998, US Department of Agriculture (USDA) Wildlife Services has tested over 90 chemical agents (agricultural pesticides and pharmaceutical and household products) and 170 chemical formulations as potential frog toxicants. Only eight chemical products were highly effective (>80 per cent laboratory efficacy) and since 2001 only three (caffeine, hydrated lime and citric acid) were at various points in time approved for frog control.

While caffeine was very effective, it was only legal for use for registration and testing from 2001 to 2002, and never received government approval for more widespread use, primarily because of concerns regarding potential human health effects. Hydrated lime (3 to 6 per cent solutions) was also found to be highly effective, and legal for use from 2005 to 2008. Homeowners like it because it is inexpensive (~\$0.02 liter^{-1}), but it leaves a white residue on plants, which makes it undesirable in nursery settings, and there are safety concerns because of its caustic effects (Pitt and Doratt, 2005).

At this time, citric acid, a minimum risk pesticide, is the only chemical that can be used legally for controlling coquis in Hawaii without restrictions. Citric acid (8 to 16 per cent solutions) is very effective (Pitt and Sin, 2004a; Doratt and Mautz, unpublished data; Pitt and Doratt, 2006; Tuttle et al, 2008). Its drawbacks include phytotoxic effects on plants, it can leave white to yellow dots on leaves, and it is relatively expensive (~\$0.54 liter^{-1}) (Pitt and Sin, 2004b).

Hot water is also effective at killing frogs and eggs. Both sprayed hot water applied at 45ºC for three minutes and vapour heat applied at 45ºC, 90 per cent humidity will kill frogs (Hara et al, 2010). However, some plant species are sensitive to heat treatments (Hara et al, 2010).

Mechanical control has also been effective. Removing vegetation reduces the number of frogs in an area (Beard et al, 2008). Hand-capturing can effectively eliminate frogs if few are present (Beard, 2001). Traps providing retreat or nest sites capture frogs and eggs but must be monitored regularly to discourage breeding (Sugihara, 2000). Traps containing calling males can attract females but do not capture many frogs, and simple barriers can be used to contain frogs in small areas.

There have been suggestions to introduce a biocontrol agent to Hawaii, especially because there are no native frogs. However, no organism with the potential to reduce coquis has been identified. For example, chytrid fungus (*Batrachochytrium dendrobatidis* or Bd), which has been implicated in global amphibian declines, was proposed for introduction, but coquis are relatively resistant (Carey and Livo, 2008); Bd is already present in Hawaiian coqui (Beard and O'Neill, 2005); and the risk of spreading Bd to other areas outweighed the potential benefit of its introduction (Beard and O'Neill, 2005).

Investigations into potential parasites for biocontrol found eight species in coqui from Puerto Rico and two different species in coqui from Hawaii (Marr et al, 2008). Of the eight species found in Puerto Rico, one nematode species was identified as having potential as a safe and effective biocontrol agent. However, further testing suggested it only had limited potential as a biocontrol agent as it reduced coqui jumping performance but did not affect coqui growth or survivorship (Marr et al, 2010).

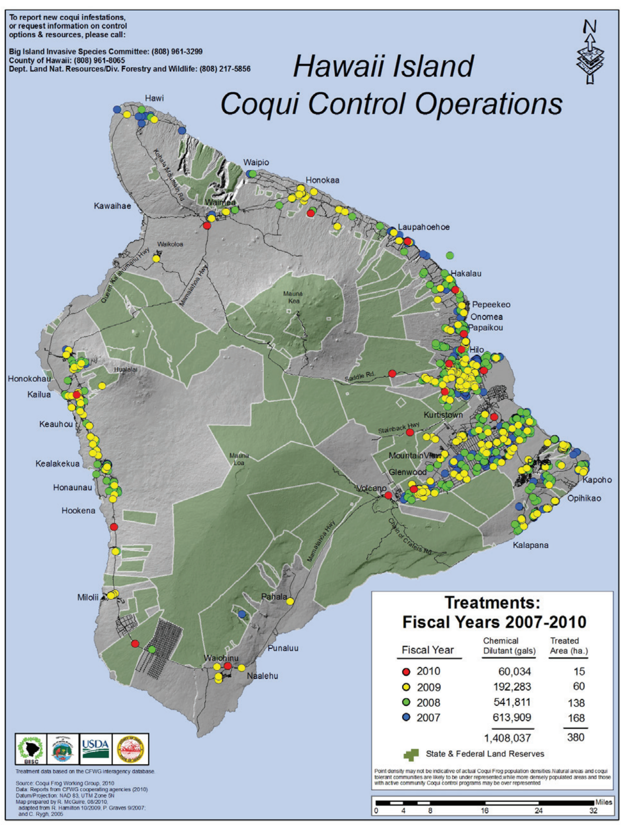
Control Effectiveness

Around 2005, the state of Hawaii began a major campaign to control the coqui. As mentioned previously, these efforts were very successful in Oahu and Kauai. For example on Oahu, control efforts on the one naturalized population were successful, with mostly ground operations (citric acid spraying, spot spraying operations and hand-capture), such that Oahu now has no naturalized populations. On Kauai, there was one naturalized population covering 6ha (Anonymous, 2010), but control efforts including large removals of vegetation and citric acid ground operations reduced this population to a very small area.

On Maui, control efforts led to the eradication of seven population centres and reduced another six populations, in addition to treating incipient populations (Anonymous, 2010). Eradication primarily occurred with ground operations of citric acid spraying, although hand-capturing was effective at removing incipient populations. On efforts in Maliko Gulch, the single, remaining large population has been problematic because of the terrain. Operations there include a variety of techniques: citric acid ground operations (citric acid fixed line delivery systems, trailer mounted storage tanks and spray systems, and spot spray operations), a high volume citric acid sprinkler system that can spray out over the gulch, aerial (helicopter) citric acid operations, and follow-up hand-capturing.

The Big Island has at least 25,000ha infested (Anonymous 2010). However, the area treated each year has been declining with reductions in funding. For example, over 415ha were treated in 2007, 340ha in 2008 and 147ha in 2009 (Figure 26.4). Over the years, treatments with citric acid, hydrated lime and mechanical techniques have been used to eradicate populations from isolated areas (such as greenhouses) and incipient populations. Aerial (helicopter) and ground operations of citric acid were effective in reducing frog densities threefold in Manuka Natural Area Reserve (Tuttle et al, 2008). Traps have been effective where there are few frogs and natural retreat sites, such as in resort areas.

The main vector for the interisland transportation of the coqui remains infested nursery products. Especially on the islands of Kauai and Oahu, which are coqui free, there needs to be effective inspection of shipments. Many shipments from the Big Island to these islands have been returned and destroyed (Anonymous, 2010). During quarantine, citric acid or, in limited areas, hot water treatments are used to eliminate frogs and their eggs from potted plants. However, these methods are not effective for large plant shipments and some growers are dissatisfied with the phytotoxic effects.



Source: McGuire et al (2010)

Figure 26.4 *Areas treated for control on the Big Island*

Opinions Regarding the Species

Coquis have been in the consciousness of Puerto Rican island dwellers for thousands of years as evidenced by the Taino Indians's (native to Puerto Rico) petroglyphs depicting coquis. Children in Puerto Rico grow up learning about these frogs, not only because of their ubiquity and conspicuous calls, but because the song of the coqui is the focus of Puerto Rican folk tales. One of these tales concludes that if coquis were ever to leave Puerto Rico, they would no longer sing. Furthermore, because Puerto Rico has no native ground mammals or other such charismatic fauna, this small frog became Puerto Rico's unofficial mascot. Thus, it probably comes as no surprise that during some of the initial control efforts, there was a campaign to have coquis shipped back to Puerto Rico. However, not everyone in Puerto Rico loves the frog, and there were individuals who called control operation managers in Hawaii to share methods for killing them.

There are also individuals in Hawaii that opposed control efforts (Kraus and Campbell, 2002). This resistance is best exemplified by the non-profit organization, the Coqui Hawaiian Integration and Reeducation Project (or CHIRP), which has a 30ha Coqui sanctuary in the south-eastern part of the Big Island. In addition to CHIRP, there are many individuals who opposed coqui control in their local community, and have been resistant to the community groups working to control coquis on their properties. Resistance to control likely has many roots, from those who: (1) generally protest the control of any organism, but particularly vertebrates; (2) enjoy the call and species; (3) do not understand the problems associated with non-native species, especially when amphibians are declining globally; (4) believe coquis might control unwanted pests; and (5) do not approve of the funds and effort spent on control, especially when it involves placing chemicals in the environment or cutting down vegetation.

By contrast, there has been a lot of public support to control coquis in Hawaii. This is best exemplified by community groups such as the Kaloko Mauka Coqui Coalition, Kohala Coqui Coalition and Volcano Volunteer Coqui Patrol. These and other similar community associations organize themselves to control local infestations. The groups raise funds to rent or purchase equipment to control coquis, and have invested endless hours of volunteer time monitoring and controlling populations. For example, the groups received 80 awards up to $5000 from the County of Hawaii in 2006 and 2007 for chemicals, safety equipment and other expenses to control frogs (Anonymous, 2010). In fact, much of the control efforts on the Big Island have been conducted by these groups; in 2008, 43 per cent of land treated was done by community associations (Anonymous, 2010). Coqui control groups have many motivating factors, including keeping yards and forests near their homes quiet, improving quality of life (i.e. sleeping better) and maintaining property values, but some of these individuals also understand the coqui is non-native to Hawaii and believe it does not belong there.

As long as coquis and people have interacted there have been strong feelings about them. At this point in time, it is unlikely that the coqui will be eradicated from the Hawaiian Islands. With this invasive species, social issues will play a role in the final outcome.

Acknowledgements

Support for this research came from the Jack Berryman Institute at Utah State University, the US Fish and Wildlife Service, Hawaii Invasive Species Council, and USDA/NWRC/APHIS/Wildlife Services.

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First published 2011
by Earthscan
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

Simultaneously published in the USA and Canada
by Earthscan
711 Third Avenue, New York, NY 10017

Earthscan is an imprint of the Taylor & Francis Group, an informa business

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British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging in Publication Data
A handbook of global freshwater invasive species / [edited by] Robert A. Francis.
p. cm.
Includes bibliographical references and index.
1. Introduced freshwater organisms. I. Francis, Robert A.
QH96.8.I57H36 2011
333.95'23091692–dc23
2011008847

ISBN 978-1-84971-228-6 (hbk)

Typeset in Garamond
by Domex e-Data, India