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FrogID: Citizen Scientists Provide Validated Biodiversity Data on Frogs of Australia

Jodi J.L. Rowley[1,2,4], *Corey T. Callaghan*[2], *Timothy Cutajar*[1,2], *Christopher Portway*[1], *Kathy Potter*[1], *Stephen Mahony*[1], *Dane F. Trembath*[1,3], *Paul Flemons*[1], and *Adam Woods*[1]

[1]*Australian Museum Research Institute, Australian Museum, 1 William Street, Sydney, New South Wales 2010, Australia*
[2]*Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales 2052, Australia*
[3]*Natural Sciences, Museum and Art Gallery of the Northern Territory, Darwin, Northern Territory 0801, Australia*
[4]*Corresponding author, e-mail: jodi.rowley@austmus.gov.au*

***Abstract*.—There is an urgent need for comprehensive global biodiversity data, particularly for highly threatened taxa such as frogs. Some of the most dramatic frog population declines, globally, have occurred in Australia, but logistical difficulties of surveying frogs (i.e., the large size of Australia and remoteness within it) have limited our knowledge of biodiversity. Citizen science projects have recently facilitated the collection of broad-scale biodiversity data, but the application of citizen science data collection to frogs has lagged behind other taxa. Citizen science projects targeting frogs have been successful in collecting occurrence data, but typically rely on species identification via user-submitted photographs. Photographs of frogs can be difficult to identify to species and may also inadvertently encourage handling of frogs. We developed FrogID, an expert validated biodiversity database of frog occurrences in Australia, reliant on acoustic validation. FrogID uses smartphone technology, allowing participants to submit recordings of calling frogs, providing a biodiversity database with geo-referenced frog species records, and a digital collection of frog calls. In a short time, FrogID has allowed us to collect data on rare and threatened frog species, document the decline of native frog species from parts of their range, and detect invasive species, including native species that have established populations outside their native range. In this paper, we (1) introduce FrogID, including technical details, (2) highlight preliminary findings, and (3) identify potential future uses of the data.**

Key Words.—acoustic; amphibian; bioacoustic; citizen science; smartphone; technology

Introduction

The global loss of biodiversity is one of the most urgent environmental problems, threatening to interfere with basic ecological functions (Barnosky et al. 2012; Dirzo et al. 2014; Ceballos et al. 2015). Current species extinction rates are dramatically higher than pre-human background rates (Pimm et al. 1995; Ceballos et al. 2015). To stem the loss of biodiversity, we must prioritize conservation efforts; however, the conservation prioritization process requires an accurate understanding of biodiversity and how it varies through space and time (Chapman and Busby 1994; Graham et al. 2004; Freitag and Van Jaarsveld 1998). Deficiencies in both the quality and availability of biodiversity data hampers our current ability to make data-driven conservation decisions including land-use planning, protected area network design, and species conservation assessments and management (Chapman and Busby 1994; Graham et al. 2004; Balmford et al. 2005). As such, there is an urgent need for more comprehensive global occurrence data (Haila and Margules 1996; Van Jaarsveld et al. 1998; Geijzendorffer et al. 2016). This is particularly urgent for highly threatened taxa, including frogs, which are among the most threatened groups of animals on the planet (International Union for Conservation of Nature [IUCN] 2018). Globally, of the almost 7,000 frog species known (Frost, Darrel R. 2018. Amphibian Species of the World: An Online Reference. Version 6.0. Available from http://research.amnh.org/herpetology/amphibia/index.html [Accessed 22 October 2018]), at least 30 species have been driven to extinction in the last several decades and almost a third are currently considered at risk of extinction (IUCN 2018). Frog populations are being impacted by numerous and often synergistic threats including habitat loss and modification, disease, harvesting, and invasive species (Collins and Storfer 2003; Stuart et al. 2004).

Some of the most dramatic frog population declines and extinctions documented have occurred in Australia. At least four frog species are considered officially extinct (Department of the Environment and Energy [DEE] 2018. Environment Protection and Biodiversity Conservation Act 1999 List of Threatened Fauna. Available from http://www.environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl [Accessed 1 October

2018]), with three of these considered so under global assessment (IUCN 2018), and others are missing, feared extinct. Over 20% of all Australian frog species assessed are considered threatened globally (IUCN 2018), and yet the frog fauna of the country remains incompletely known. At present, 240 native frog species are known from Australia, but in the last decade alone, 18 species of frog have been described (Frost. 2018. *op. cit.*), representing an 8% increase in the known frog species diversity. This paradoxical increase is partly due to the incorporation of molecular and bioacoustics data in delineating species (e.g., Anstis et al. 2016; McDonald et al. 2016), and partly due to increased survey efforts in remote areas (e.g., Hoskin 2013), a global phenomenon (e.g., Catenazzi 2015).

Logistical constraints lead to a lack of information.—One of the biggest obstacles to frog conservation in Australia is our lack of knowledge, primarily a result of logistical constraints. To understand the current biodiversity of the country, and to prioritize efforts to conserve it, further survey work is urgently needed, particularly across inland Australia (Slatyer et al. 2007); however, access limitations complicate this. The total landmass of Australia is 7,692,024 km^2 and more than 86% of Australia is classified as remote or very remote (Glover and Tennant 2003). Particularly in arid areas, frog species may only be detectable after rainfall events, making timely visits to sites for informative surveys even more problematic. In these cases, local residents have an advantage over professional scientists in terms of data collection. In Australia, many frog species have few records, and even fewer recent records. For example, based on the Atlas of Living Australia (ALA) data, the national aggregate database of biodiversity data, 40% of all native frog species have fewer than 10 total records since 2010, and 20% have none (Atlas of Living Australia. 2019. Atlas of Living Australia [ALA]. Available from http://www.ala.org.au [Accessed 18 January 2019]). Large areas of Australia have no frog records (ALA. 2019. *op. cit.*), despite frogs being present throughout the continent, with the exception of a section of the Nullarbor Plain of South Australia and Western Australia, where frogs are thought to be truly absent (Cogger 2018).

Citizen science provides broad-scale empirical data.—Citizen science involves a partnership between scientists and the community, specifically non-scientists, in which participants collect, analyze, and interpret data for scientific research (Jordan 2012; Toomey and Domroese 2013; Johnson et al. 2014). Citizen science is helping to combat logistical constraints placed on professional scientists (Silvertown 2009; Jordan et al. 2015). Citizen scientists are increasingly contributing to our collective knowledge of biodiversity (Pimm et al. 2014; Ganzevoort et al. 2017; Stephenson et al. 2017) on an unprecedented spatial scale. For example, global projects such as iNaturalist (www.inaturalist.org) and eBird (Sullivan et al. 2014) are collecting millions of observations annually. These data are often spatially and temporally biased (Boakes et al. 2010; Courter et al. 2013), but in general, citizen science data have been shown to be comparable with those data collected by professional scientists (Aceves-Bueno et al. 2017) for certain kinds of data.

Citizen science and frogs.—The application of citizen science data collection to frogs has historically lagged behind other, less threatened taxa (i.e., birds, insects, plants) (Geijzendorffer et al. 2016); however, various citizen scientist projects targeting frogs (or most often frogs, other amphibians, and reptiles) exist, and have resulted in the collection of a large number of frog records on a local, state, or national level (for examples, see Table 1). In addition to these herpetologically focused projects, several citizen science projects that are taxonomically broad and global have also been successful in collecting large volumes of frog records (e.g., iNaturalist: http:// https://inaturalist.org; QuestaGame: https://questagame.com/; and Herpmapper: https://www.herpmapper.org/).

Many existing citizen science projects targeting frogs require participants to undergo training and follow standardized survey protocols. This additional complexity is likely to result in fewer participants (Bonney et al. 2009; Hobbs and White 2012; Frensley et al. 2017). More recently, there has been a shift towards participants submitting opportunistic photographs of animals to citizen science projects, thereby removing the need for participant training or standardized protocols. However, many frog species are small and camouflaged, rendering them difficult to visually locate and photograph, particularly without disturbing their habitat. Even when photographed, the identification of certain frog species can be difficult or impossible. Many photographs do not provide enough detail (i.e., thigh coloration, belly patterning) to identify morphologically cryptic species (species that are similar or nearly identical in appearance). More importantly, relying on photographic submissions is likely to increase the handling of frogs, with implications for disease transmission. For example, 6% of the 892 photographic submissions of frogs from Australia in 2017 submitted to iNaturalist showed frogs being handled with bare hands (iNaturalist.org. 2018. iNaturalist. Available from http://www.inaturalist.org [Accessed 1 October 2018]). Despite these challenges, the majority of existing frog-focused citizen science initiatives focus on photographs being submitted and identified to species. Despite its inherent usefulness in delineating frog species (see below), to our knowledge, interspecific variation in male

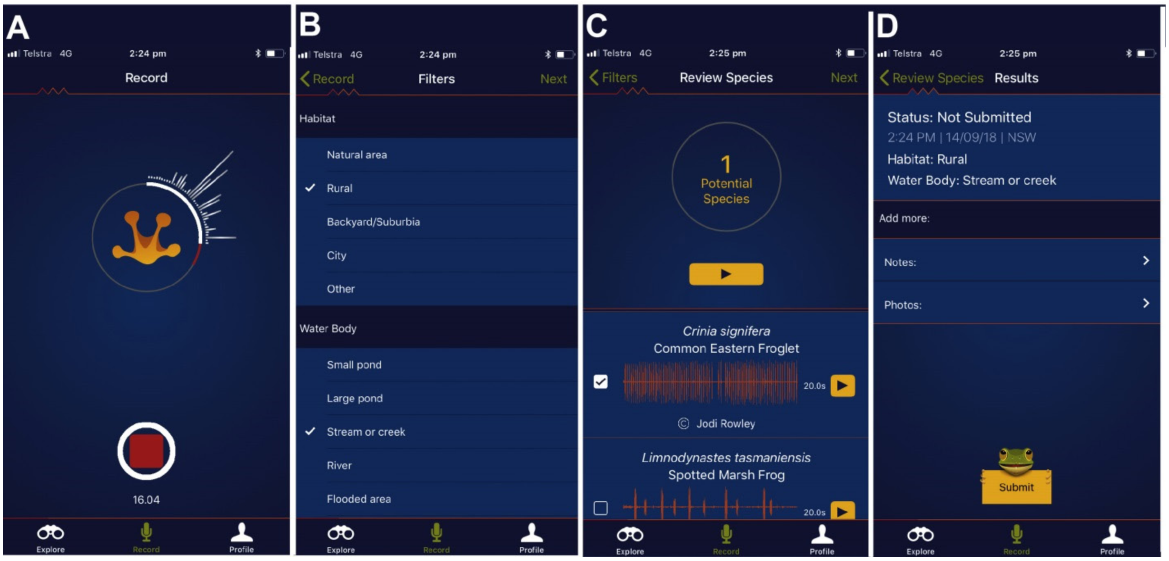

Figure 1. User interface of the FrogID app (iOS, version 1.2.1). (A) Recording frog call, (B) selecting habitat filters (optional), (C) selecting frog species (optional), and (D) submitting recording (note option to add notes and photos).

frog advertisement calls has only been incorporated into two citizen science projects in Australia focusing on capturing recordings of frogs: Frog Census in Victoria and FrogWatch SA in South Australia (Table 1).

***Acoustic data: virtual vouchers of frogs*.**—The male advertisement call is, by far, the most common frog call heard (Wells 1977). It is often repetitive and serves to attract potential mates and convey territorial information (Köhler et al. 2017). In frogs, the advertisement call communicates species-specific information, thereby serving as a premating isolation mechanism (Blair 1964; Littlejohn 1969). As a result, advertisement calls are commonly used for frog species identification in surveys (Heyer et al. 2014) and in the description of new species (Littlejohn 1969; Rowley et al. 2016; Köhler et al. 2017).

Frog advertisement calls are useful in detecting frog species more easily and efficiently than by visual searches, and disturbances to the frog and its habitat are minimized. These calls are especially useful in detecting small or difficult to locate frog species, and in identifying morphologically cryptic species, where visual identification is difficult. All known frog species in Australia have audible calls, and most are readily distinguished by their advertisement call, with only a few difficult to identify to species via their calls (e.g., several species of the genus *Pseudophryne* in the places where they co-occur; Pengilley 1971). Further, several Australian frog species that are morphologically indistinguishable from related species can be identified to species by their calls (e.g., *Litoria jungguy* and *Litoria myola*; Donnellan and Mahony 2004; Hoskin 2007). As frogs call almost exclusively from breeding sites, localities of calling frogs also provide vital information on their breeding habitats, critical for conservation, and breeding times, vital for understanding the impact of climate change on frog species.

***Objectives*.**—The purpose of this paper is to introduce FrogID, an Australia-wide citizen science initiative with the aim of informing the conservation of this poorly-known and threatened group of animals. Launched on 10 November 2017 and led by the Australian Museum, FrogID is the first citizen science initiative aimed at capturing validated biodiversity data on Australian frogs on a national scale. The project relies on citizen scientists recording frog advertisement calls using the FrogID smartphone app. These audio recordings are then used to create a database of frog species records and a digital library of frog call recordings. Specifically, we (1) detail the methodology, data quality, and workflow of the project; (2) identify preliminary findings; and (3) highlight future uses of the data in understanding and conserving frogs of Australia.

FrogID: Creating an Expert Validated Biodiversity Database

***Using technology to capture calling frogs*.**—The FrogID project collects data via a smartphone application (app) using both iOS (Apple, Cupertino, California, USA) and Android (Google, Mountain View, California, USA) operating systems, allowing participants to submit recordings of calling frogs. FrogID participants record 20–60 s of audio using the app (Fig. 1A). Once a recording is made, participants may select habitat type (natural area, rural, backyard/suburbia, city, other) and water body (small pond, large pond, stream or creek, river, flooded area, no visible water bodies; Fig. 1B).

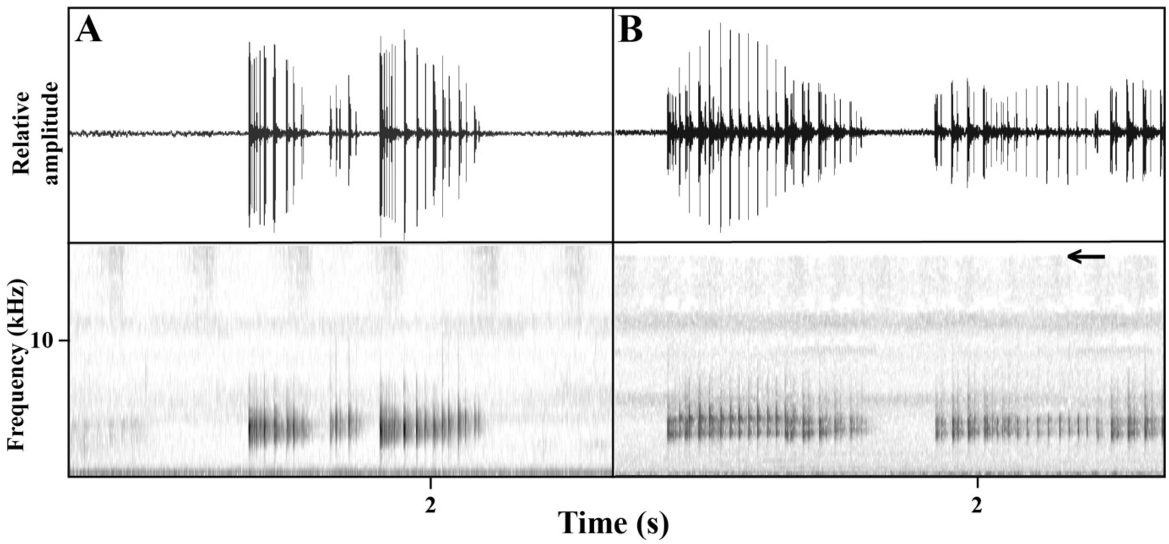

Figure 2. Comparison of quality of call recordings of the same Remote Froglet (*Crinia remota*) recorded under the same conditions, but several minutes apart (therefore capturing different individual calls), recorded with (A) professional recording equipment (H4NPro with Rode NTG-2 directional microphone, 96kHz sampling rate, 24 bits, saved as .wav file) and (B) smartphone using FrogID (iPhone 7; Apple Inc., Cupertino, California, USA, and built-in microphone, 44.1kHz sampling rate, saved as .aac file; arrow denotes upper limit of frequency detection at approximately 17 kHz). We created spectrograms with fast-Fourier transform (FFT) of 512 points, 50% overlap, and 172 Hz grid-spacing, using Hanning windows in Raven Pro 1.3 software (http://www.birds.cornell.edu/raven).

Participants are then presented with a list of all frog species likely to occur in the geographic location of the recording (based upon records in the ALA and expert opinion), narrowed further by their selected habitat and water body categories (if selected). Participants can then play example calls and may select the frog species that they believe they recorded (Fig. 1C). Notes and photos can also be added before submission (Fig. 1D). All participant selections are optional. The time, date, and geographic location (latitude, longitude, and an estimate of precision of geographic location) are automatically added by the app at the time of recording. The estimate of the horizontal accuracy of this location is given as a radius of confidence, in meters (using horizontalAccuracy: iOS, or getAccuracy: Android). Participants can submit these recordings immediately in areas with mobile phone data or internet access, or the recordings will submit later, when the app is opened again in areas with mobile phone data or internet access.

Recordings made with the FrogID app are stereo Moving Picture Experts Group Advanced Audio Coding (MPEG AAC) audio (mp4a) files with a sampling rate of 44.1 kHz. The quality of recordings submitted to FrogID varies considerably based upon phone model, proximity to calling frogs, and background noise. The model of phone impacts detection range and frequency response of any audio signal recorded (Zilli 2015). Almost all smartphone models have microelectromechanical systems (MEMS) microphones that have a flat frequency response up to a threshold (Kardous and Shaw 2014). Frequencies above 17 kHz are not represented in calls submitted to FrogID (Fig. 2), but all known Australian frogs have calls below 10 kHz (Loftus-Hills 1973; Jodi Rowley et al., unpubl. data), and most are below 5 kHz

Table 1. Examples of citizen science projects targeting frogs or targeting frogs and other amphibians and reptiles.

Program	Reference
ACT FrogWatch	https://ginninderralandcare.org.au/frogwatch/frogwatch-2
Carolina Herp Atlas	https://www.carolinaherpatlas.org
Frog Census	https://www.melbournewater.com.au/community-and-education/waterwatch-program/frog-census
Frogwatch Canada	https://www.naturewatch.ca/frogwatch
FrogWatch SA	https://www.frogwatchsa.com.au
Frogwatch USA	http://www.frogwatch.org
National Amphibian & Reptile Recording Scheme	http://narrs.org.uk/index.php
North American Amphibian Monitoring Program	https://www.usgs.gov/centers/pwrc/science/north-american-amphibian-monitoring-program
Pennsylvania Amphibian & Reptile Survey	https://paherpsurvey.org

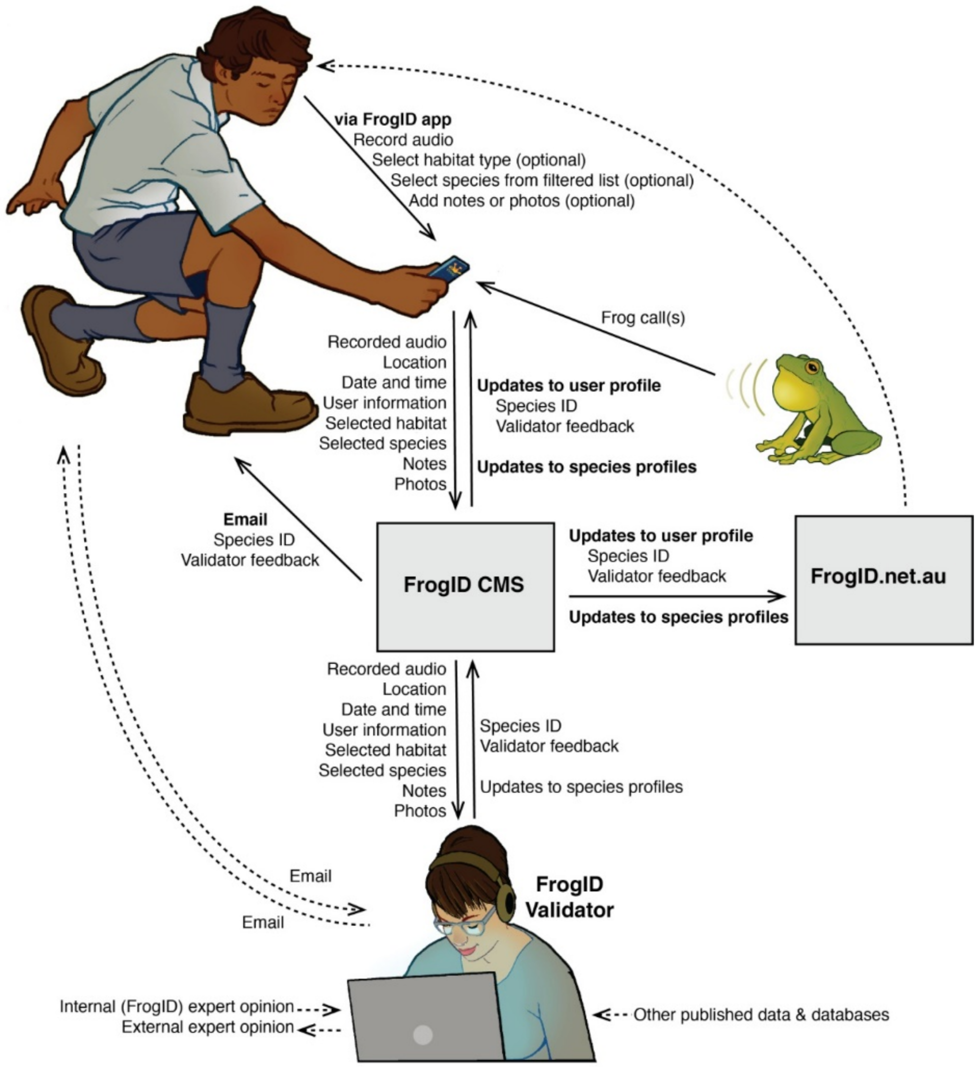

Figure 3. Workflow of FrogID. The FrogID project collects data via a smartphone app allowing users to submit recordings of calling frogs. Once FrogID users submit recordings and associated data, they are received in the cloud-based Content Management System (CMS) and are identified to species by FrogID validators. Species identifications and any written feedback from FrogID validators for each submission are returned to users via email and via the profile section of the app and website (www.frogid.net.au).

(Loftus-Hills and Johnstone 1970; Heffner and Heffner 2007). External microphones may improve audio quality (Kardous and Shaw 2016), but good quality recordings may be obtained without their use (Fig. 2). In recent years, publications formally describing advertisement calls have even used smartphone recordings of frog calls (e.g., Chaudhury et al. 2016).

Identification of frog calls.—Once FrogID users submit recordings, the cloud-based FrogID Content Management System (CMS) receives and queues them for validation (species identification; see FrogID workflow steps in Fig. 3). FrogID validators (scientists with expertise in frog species identification via advertisement calls) log in to the CMS, listen to these recordings, and can view associated data. Recordings can also be downloaded and visualized in sound analysis software and further compared to known species or sent to other frog call experts. FrogID validators then use the audio and associated information, plus a reference call library, to identify the frog species calling in the recording. If no frogs are heard calling (e.g., a FrogID user recorded an insect), submissions are identified as Not a Frog. If the recording is not sufficient to identify species (i.e., too short in duration, too much other noise in the recording), we identify the submission as Unidentified Frog. We return species identifications and any written feedback from FrogID validators for each submission to the contributor via email and via the profile section of the app and website (www.frogid.net.au). We flag records that fall outside of known geographic ranges for each species and confirm species

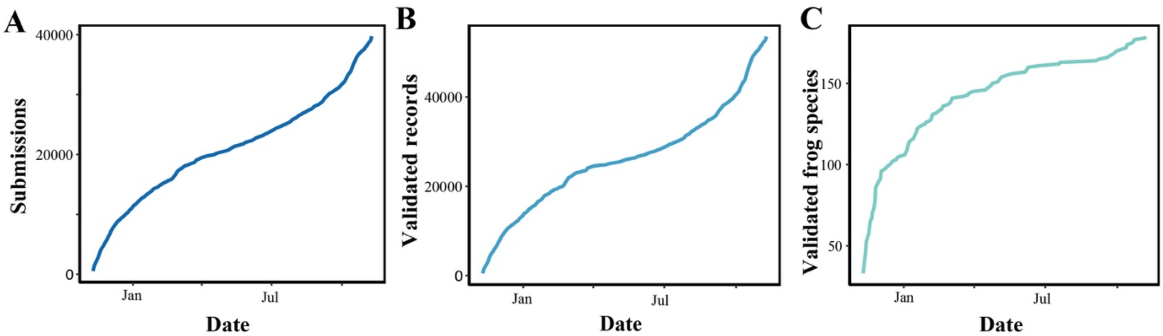

FIGURE 4. Cumulative number of (A) submissions, (B) validated records of frogs, and (C) validated frog species received from 10 November 2017 to 9 November 2018 in Australia.

identities, often with feedback from local experts and the contributor. FrogID submissions typically contain the advertisement calls of more than one species of frog, resulting in more validated records of frogs than submissions.

Submissions vary in amplitude, and different frog species may be heard loudly (i.e., frogs in close proximity to the recorder) or faintly (i.e., frogs at a distance from the recorder). Although smartphone microphones can capture sound as low as 30 dB SPL (Kardous and Shaw 2014), noise propagation through the air is complex and difficult to model (Kanjo 2010). The detection range of frogs from the point of recording is therefore difficult to determine and is likely to vary significantly depending on the frog species, phone model, whether an external microphone is used, phone position, habitat structure, and background noise (e.g., wind and rain, road traffic, and user movements).

FrogID: Preliminary Findings

From the launch of FrogID on 10 November 2017 until 9 November 2018 (one year), FrogID received > 53,000 submissions, about 33,000 of which included identifiable calls of frogs. On 15 January 2019, these submissions had resulted in 66,790 validated records of frog species across Australia. This is a significant contribution to our understanding of frogs in Australia, equivalent to > 13% of all frog records in the ALA, collected over the last 240 y or so (ALA. 2019. *op. cit.*).

FrogID had 16,195 registered users as of 9 November 2018, with 6,510 people having submitted recordings with calling frogs. The majority of recordings have been submitted by a relatively small percentage of users, with just 296 people (i.e., 5% of people who submitted calls) accounting for over half of all frog call submissions, supporting the notion that citizen science projects are driven by Power Users (Wood et al. 2011). Submissions and resulting validated frog records were most frequent during the months of October and November, with a peak of 844 validated frog records per day on 11 November 2018 (Fig. 4A-B).

FrogID submissions have come from across Australia but, not surprisingly, are biased towards populated areas, with 41% of all frog records from the 0.3% land area with ≥ 100 people per km^2 (Fig. 5). As of 9 November

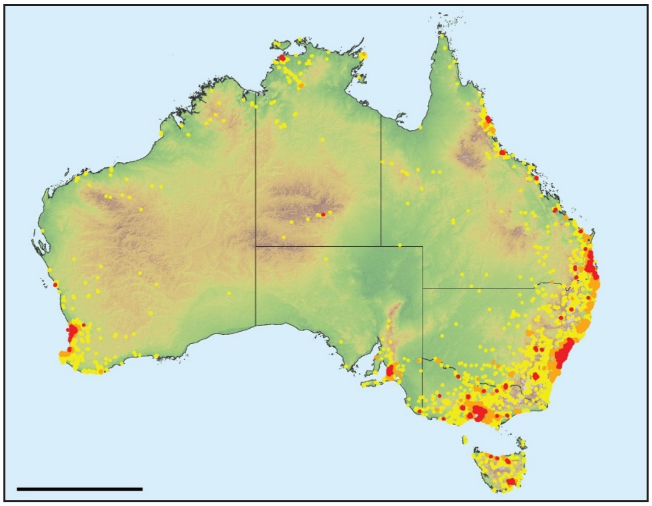

FIGURE 5. Map of Australia showing the distribution of all verified frog recordings submitted to FrogID from 10 November 2017 to 9 November 2018. Recordings are graded by the number of people/km^2 (https://doi.org/10.7927/H4DZ068D) in the area where they were taken: ≥ 100 (41% of recordings) shown in red, 10–99 (22% of recordings) in orange, and < 10 (37% of recordings) in yellow. Scale bar is 1,000 km.

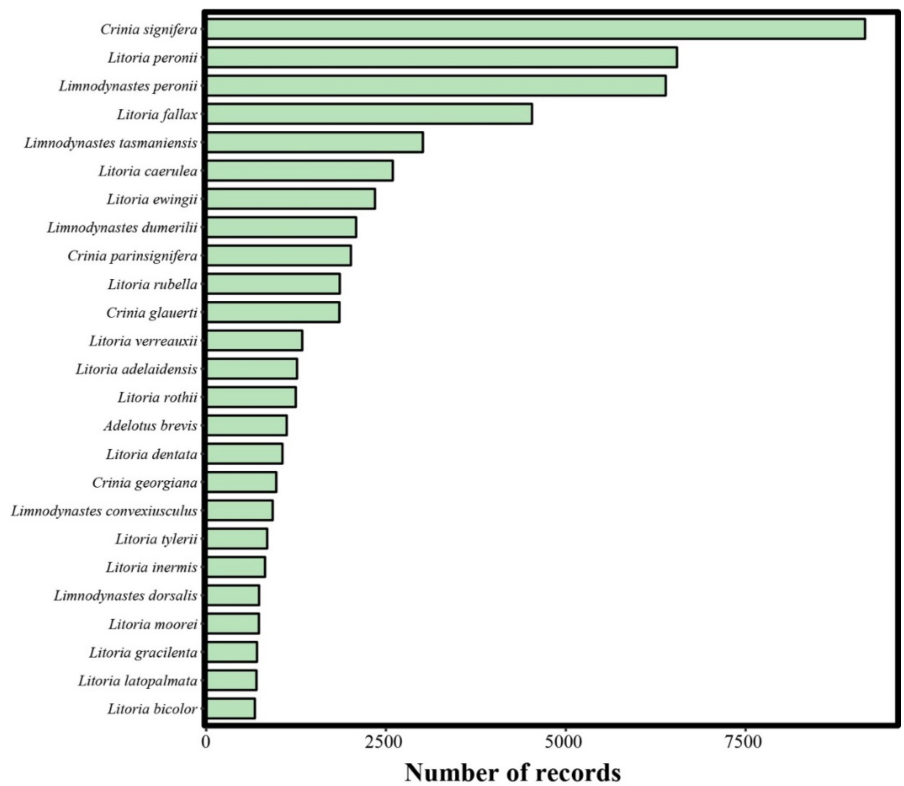

Figure 6. Number of records in Australia submitted to FrogID for the top 20 frog species from 10 November 2017 to 9 November 2018.

2018, we had detected 175 (73%) of 240 known native frog species, plus the introduced Cane Toad (*Rhinella marina*). The increase in number of species detected via FrogID submissions has slowed over time as the most widespread and easily accessible species have been detected (Fig. 4C). The frog species recorded are heavily skewed towards a small subset of species that are widely distributed and often in association with human-modified environments, with the 10 most commonly recorded species making up 61% of all records (Fig. 6). Two species have been recorded in over 5,000 submissions, the Common Eastern Froglet (*Crinia signifera*) and the Striped Marsh Frog (*Limnodynastes peronii*; Fig. 6). Sixty-two species have been recorded fewer than 10 times.

Frog species that are small, difficult to visually locate, and challenging to identify based upon appearance are well-represented. Individuals in the genera *Crinia*, *Geocrinia*, and *Uperoleia*, typified by small, morphologically cryptic species that are difficult to visually detect, account for 30% (15,959) of all FrogID frog records. This compares to only 5% (28) of the submissions from Australia identified to species in iNaturalist in 2017 (iNaturalist.org. 2018. *op. cit*.) and 4% (13) in QuestaGame (QuestaGame 2018. QuestaGame. Available from http://www.questagame.com. [Accessed 1 October 2018]). The records received to date contribute substantially to our understanding of frog biodiversity in Australia.

Detecting breeding populations of rare and threatened species.—FrogID has detected 28 species listed as threatened globally (IUCN 2018) and 13 species listed as nationally threatened (DEE. 2018. *op. cit*.). The threatened species for which we have the most records to date is the Sloane's Froglet (*Crinia sloanei*), a small, difficult to visually detect species from inland New South Wales (NSW) and Victoria. This species has a draft conservation status of Endangered nationally (DEE. 2018. *op. cit*.). Since launch, we have received 292 records of the species, primarily as a result of the group Sloane's Champions, initiated by the NSW Office of Environment and Heritage and Woolshed Thurgoona Landcare Group. The number of records obtained are approaching the total number of records ever documented for the species (348; ALA. 2019. *op. cit*.), and many existing records of the species in the north of its range are likely to be misidentification of other, morphologically similar, species in the same genus (Spark 2015).

Although there has been a bias towards recordings of relatively common and widespread species that occur in populated areas, the FrogID data to date include records of species that are poorly known and rarely

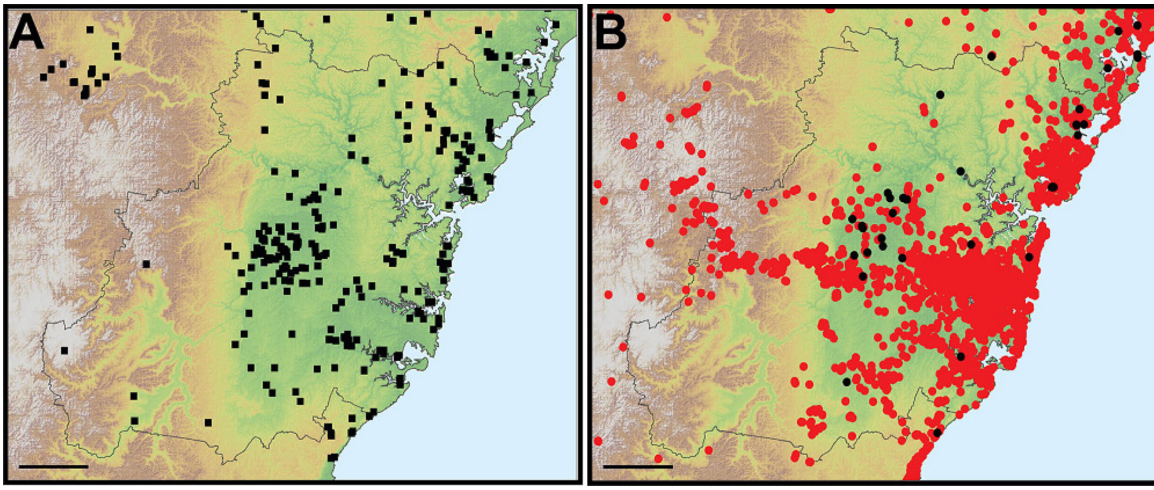

Figure 7. (A) All records of the Green Tree Frog (*Litoria caerulea*) from the Atlas of Living Australia, and (B) verified records for all species from FrogID (red circles) and all records of the Green Tree Frog verified from these records (black circles; n = 44) in Greater Sydney from 10 November 2017 to 9 November 2018. The Greater Sydney area, delineated according to the Australian Bureau of Statistics (http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%202016?OpenDocument), is outlined in black. Scale bars are 25 km.

documented, primarily due to access difficulty and remoteness. For example, we have received 10 records of the Small Toadlet (*Uperoleia minima*), 11% of the 88 records of the species on ALA (ALA. 2019. *op. cit*.), and three records of the Black Mountains Boulder Frog (*Cophixalus saxatilis*), 7% of the 43 on the Atlas of Living Australia (ALA. 2019. *op. cit*.). These records increase our ability to make data-driven management decisions for these poorly known species.

Data on disappearing frogs.—The Australian Green Tree Frog (*Litoria caerulea*) was widely distributed throughout the Sydney area in the late 1800s and early 1900s (Fig. 7A). Green Tree Frogs were collected or reported from central Sydney suburbs, including Sans Souci, Botany Bay (Australian Museum, Sydney [AMS] specimen registration numbers AMS R 5177; in the year 1911), Randwick (AMS R 5088; 1911), Waverley (AMS R1899, 1900, 1875; about 1895), Bondi (AMS R 5092; 1911), Mosman (AMS R2575, 1899), and Curl Curl (Copland 1957; AC 5447). There are 328 records of the Green Tree Frog from the greater Sydney area in the Atlas of Living Australia (ALA. 2019. *op. cit*.), and in 1922, Harrison (1922) noted that the species was "very generally distributed both in gardens and in the bushland surrounding them" in Mosman, with "perhaps a hundred frogs" observed on a night (Harrison 1922, p. 21). Although there are anecdotal reports of the decline of the Green Tree Frog in Sydney (James 1997; White and Burgin 2004; Department of Environment and Climate Change 2007), FrogID provides compelling evidence of this decline. Of the 7,120 FrogID recordings from the Greater Sydney area (defined according to the Australian Bureau of Statistics: http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%202016?OpenDocument), we received only 52 recordings of the Green Tree Frog, most from outside Sydney itself, in the local government areas of Hawkesbury, Gosford, and Wyong (Fig. 7B). We received no recordings of Green Tree Frogs from any of the inner Sydney suburbs with historical records listed above. Green Tree Frogs are a loud species commonly associated with human settlements and, country-wide, were the seventh most common species identified from recordings submitted to FrogID, with 2,009 records (Fig. 6). The Green Tree Frog was the most common frog species recorded in Darwin, and the third most common species recorded in the Greater Brisbane area. We commonly heard the species in choruses of multiple species and detected it in submissions with up to 10 other frog species calling. Given their high detectability, even within urban areas, the paucity of records from within the Greater Sydney area is likely a true reflection of their decline throughout much of the Greater Sydney area.

Detecting invasive species.—The impacts of invasive species on ecosystems is a serious conservation issue (Byers et al. 2002). Species that establish populations outside their native range may impact ecosystems via predation or poisoning of native species, competition with native species, the introduction of pathogens and parasites, and genetic contamination (Kraus 2007). The early detection of invasive species increases the chances that the population can be controlled (Mehta et al. 2007) and understanding the distribution and impact of established invasive species contributes towards their effective management.

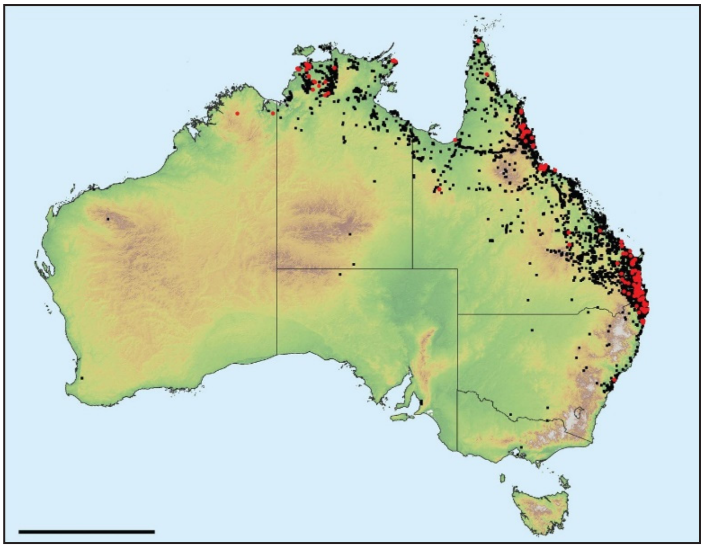

Figure 8. All records of the Cane Toad (*Rhinella marina*) from Atlas of Living Australia (black squares) and all verified recordings of the Cane Toad (*Rhinella marina*) submitted to FrogID from 10 November 2017 to 9 November 2018 (red circles). Scale bar is 1,000 km.

The only exotic invasive frog species known to have established self-sustaining populations in Australia is the Cane Toad. FrogID has received 438 submissions of the Cane Toad from across its range in Queensland, NSW, the Northern Territory, and Western Australia (Fig. 8). Three records obtained from Western Australia (Kunanurra and Drysdale River) are particularly important. The species was first detected in Western Australia in 2009 (Department of Environment and Conservation 2014), and priorities for the state include frontline survey and mapping to ensure up-to-date information on Cane Toad movements and monitoring changes in populations of native species before and after the arrival of Cane Toads. The ALA includes only seven records of the Cane Toad in Western Australia (ALA. 2019. *op. cit*.).

Native frogs detected outside their native range.— One of the most surprising results to date from calls submitted to FrogID is the number of records of native frog species detected calling from well outside their known range. The greatest number of calling sites detected far outside the native range were for the Eastern Dwarf Tree Frog (*Litoria fallax*). This species is frequently transported, along with horticultural products and fresh fruit, to cities and towns outside its known natural range, and has established a breeding population in Guam in the western Pacific Ocean (Christy et al. 2007). It was first recorded outside its native range in Australia in 1999, in Moorabbin, Melbourne (Gillespie and Clemann 2000), and has since established self-sustaining populations elsewhere in Melbourne, and in north-east Victoria (Michael and Johnson 2016). We received 17 recordings of the Eastern Dwarf Tree Frog from Victoria, up to 400 km from the southern edge of its native range near the New South Wales/Victoria border (Fig. 9A). In addition to detecting previously reported populations, recordings of the species were submitted to FrogID from Lower Plenty, fewer than 5 km from reported localities, Yackandandah, more than 10 km from reported populations in Baranduda and Kiewa, and Whittlesea, more than 25 km north of known populations in Melbourne. An additional recording of this species came from Australian Capital Territory, approximately 50 km from its native range.

Three other species of tree frog have also been detected south of their native ranges via FrogID submissions. We received five recordings of the Red-eyed Tree Frog (*Litoria chloris*) from two sites about 3 km apart in Nowra, 152 km from its known native range in NSW (Fig. 9B). The Red-eyed Tree Frog has been reported in the Nowra region since 2011 (ALA. 2019. *op. cit*.). We received recordings of the Graceful Tree Frog (*Litoria gracilenta*) from two FrogID users in January-March 2018 (five submissions over four nights) at a single site in the northern beaches of Sydney, 136 km from its known range (Fig. 9C). Several of the submissions were of multiple frogs calling, records were up to 500 m apart, and numbers were estimated by a FrogID user as in the dozens. We also received a single record of the Graceful Tree Frog from the Central Coast of New South Wales, about 90 km from their known native range. These records are the first documentation of apparently established populations of Graceful Tree Frog outside of its native range, although there are two records of the species from Sydney from 1987 and 1999, the latter being a frog found at Flemington Markets (ALA. 2019. *op. cit*.). Lastly, we received a single recording of the Red Tree Frog (*Litoria rubella*) from Melbourne, about 400 km from its known range (Fig.

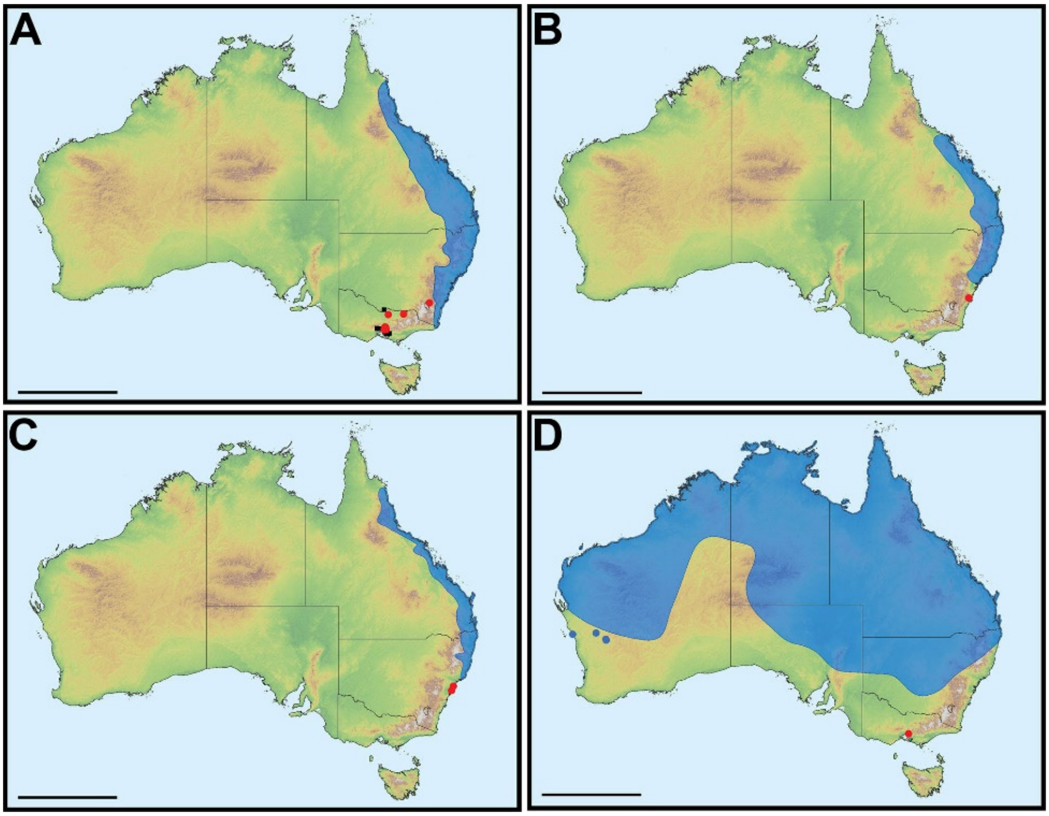

Figure 9. Examples of native frog species in Australia that have been detected calling outside their native range. Native ranges of frogs (from FrogID, derived from Atlas of Living Australia, scientific literature, and expert opinion) are shown in blue; red circles are FrogID records outside the native range of the species. (A) The Eastern Dwarf Tree Frog (*Litoria fallax*), detected in the Australian Capital Territory, about 50 km outside its native range, and in Victoria, about 245–400 km outside its native range (black squares are previously known localities where the this species has become established outside its native range; see text), (B) the Red-eyed Tree Frog (*Litoria chloris*), detected in Nowra, New South Wales, approximately 152 km outside its native range, (C) the Graceful Tree Frog (*Litoria gracilenta*), detected in the Central Coast and in Sydney, New South Wales, approximately 92–136 km outside its native range, and (D) the Red Tree Frog (*Litoria rubella*), detected in Melbourne, Victoria, approximately 400 km outside its native range. Scale bars are 1,000 km.

9D). Although there are two records of the species from Victoria from 1955 and 1957 (ALA. 2019. *op. cit*.), the accuracy and nature of these records is unknown.

These four species have all been reported previously as stowaway frogs (O'Dwyer et al. 2000), inadvertently transported outside their native range via produce or potted plants and released. The scale of these stowaway frogs is thought to be large; each year, over 7,000 frogs are estimated to be translocated with produce to Flemington Markets and major supermarkets in New South Wales alone (O'Dwyer et al. 2000). This is likely an ongoing threat to biodiversity in Australia, with invasive populations potentially impacting native frogs via competition and the introduction of disease (e.g., Hartigan et al. 2012).

Future Directions

When designing and implementing a citizen science project, a number of trade-offs need to be accounted for (Lukyanenko et al. 2016), and chief among them are the type of data collected. We designed FrogID primarily to collect presence-only data to maximize participation by volunteers (Bonney et al. 2009; Bird et al. 2014), avoiding complicated instructions which aim to collect presence-absence data. Collection of absence data would also involve volunteers frequently finding zero frogs, diminishing the likelihood they would further participate in the project. We acknowledge that for many ecological applications, presence-absence data are superior (Guillera-Arroita et al. 2015; Kissling et al. 2018), but also note that species distribution modeling techniques relying on opportunistic, presence-only, data is an area of active research (Raes and ter Steege 2007; VanDerWal et al. 2009; van Strien et al. 2013). In addition, although the FrogID protocol does not account for true absences (i.e., observers recording zero frogs in a submission), absences of frog species can be inferred from FrogID recordings. Recordings with identifiable frog calls typically include multiple species (an average of 2.2 species with a current maximum of 11 species per recording). Therefore, any species not heard calling in a recording can be considered missing from that survey (e.g., Sullivan et al. 2009), or, for frequently visited sites, absence can be inferred if, over many conditions (e.g., time of day, temperature), a species is not encountered, which increases the probability of a true absence of that species (Guillera-Arroita 2017). Future research using FrogID data may also explore the relative abundance of species calling, or calling intensity, such as the amphibian calling index (Weir and Mossman 2005). It is our hope that FrogID data will contribute to species distribution models and ecological modeling of the frogs of Australia.

In a short time, FrogID has expanded our knowledge on the known distribution and breeding seasons for several species. In the future, it will be of value to correlate this with associated weather and rainfall data to build a more detailed and accurate understanding of the timing and duration of breeding seasons for many of the frogs in Australia, fundamental life-history information that is still unknown for many species (Bury 2006). These data will be vital in understanding when frog species are most detectable, and how they are responding to a changing planet. The large number of submissions from within, and adjacent to, urban areas will enable fine-scale trends in frog species assemblages to be examined (e.g., Westgate et. al. 2015).

In addition to the biodiversity data collected through FrogID, large sample sizes of call recordings will enable the identification of potential new frog species through powerful analyses of call characteristics, especially for morphologically cryptic taxa. The digital collection of frog calls can also potentially be used to further develop machine learning techniques for automated frog call analyses (e.g., Huang et al. 2009). Ultimately, with the increase in spatially and temporally precise occurrence data and associated advertisement call recordings, researchers will be able to access unprecedented amounts of data that can directly inform frog conservation. These data can highlight key breeding sites of threatened species, or important areas of previously underestimated biodiversity can be identified and prioritized for protection and further research.

Conclusions

FrogID represents a large-scale citizen science initiative focused on collecting validated records of frogs in Australia. In one year, it has gathered > 66,000 observations: 13% of the total number of previous frog records collected in Australia over the past approximately 240 y (ALA. 2019. *op. cit*.). The project takes full advantage of widely available technology (i.e., smartphone development) and frog biology (i.e., male advertisement calls) to obtain geo-referenced biodiversity data and generate a digital library of frog call recordings. Further, use of the app is likely to discourage participants from handling or disturbing frogs while collecting data because such behavior typically causes frogs to stop calling.

FrogID is also likely to have an ongoing benefit to conservation via its impact on users (Bonney et al. 2009). In other citizen-science projects, gains in content knowledge and in understanding the nature of the scientific process have been well-documented (e.g., Brossard et al. 2005; Evans et al. 2005; Jordan et al. 2011; Toomey and Domroese 2013). FrogID is likely to train users to recognize frog calls and to distinguish them from insects and birds, and FrogID validators also provide feedback to users aimed at improving the quality of the data they collect. One of our greatest hopes is that FrogID will be an increasingly useful tool for community groups in their surveys of local biodiversity, including monitoring of threatened frog species. Some of the most valuable records submitted have been through the group Sloane's Champions, who have almost doubled the number of records of a small, threatened frog species (*Crinia sloanei*), demonstrating the usefulness of FrogID as a biological survey tool.

Citizen science is transforming our understanding of biodiversity occurrences and ecological processes (Sullivan et al. 2014). We have demonstrated that validated biodiversity records of frogs can be collected by citizen scientists using smartphones, at broad spatial and temporal scales previously unexplored. The unique ecological, biological, and conservation applications for the frogs of Australia will continue to be explored using FrogID.

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Jodi J. J. L. Rowley is the Curator of Amphibian and Reptile Conservation Biology at the Australian Museum Sydney, New South Wales, Australia and University of New South Wales, Sydney, New South Wales, Australia. Her research strives to uncover amphibian biodiversity, assess population threats and trends, and inform conservation decisions. (Photographed by Stuart Humphreys).

Corey T. Callaghan received his B.S. from Canisius College, Buffalo, New York, USA, and his M.S. from Florida Atlantic University, Boca Raton, Florida, USA. He is currently a Ph.D. candidate at University of New South Wales, Sydney, New South Wales, Australia, and a research assistant at the Australian Museum, Sydney, New South Wales, Australia. He has worked for the U.S. Fish and Wildlife Service and as a private consultant, largely focused on birds. His research is predominantly concerned with urban ecological aspects and applied use of broad-scale empirical data, including that collected by citizen scientists, in urban environments. (Photographed by Diane Callaghan).

Timothy Cutajar worked as an amphibian and reptile keeper in zoos in Australia and New Zealand from 2008–2015. He received a Bachelor of Biodiversity and Conservation in 2015 from Macquarie University, Sydney, New South Wales, Australia, and began working at the Herpetology Department of the Australian Museum, Sydney, New South Wales, Australia, as a research assistant in the same year. Tim is also currently completing an Honours degree with the University of New South Wales, Sydney, New South Wales, Australia. (Photographed by Jodi Rowley).

Christopher Portway graduated with a B.Sc. from the Australian National University, Canberra, Australian Capital Territory, Australia, in 2011. Since 2016 he has been a Research Assistant in Herpetology at the Australian Museum, Sydney, New South Wales, Australia where he helped to develop species description and mapping information for FrogID. He is currently focused on the taxonomy and conservation of Australasian frogs. (Photographed by Anusara Ratseewo).

Kathy Potter completed a degree in Linguistics in 2009 before discovering an interest in bioacoustics and amphibian research. She has been working at the Australian Museum, Sydney, New South Wales, Australia, as a Research Assistant for almost two years on a variety of projects centered around frog advertisement calls, including FrogID. Kathy also has extensive experience as a science communicator through her involvement with the Frog and Tadpole Study Group of New South Wales, Sydney, New South Wales, Australia. (Photographed by David Potter).

Stephen Mahony received a B.Sc. at the University of Newcastle, New South Wales, Australia, in 2013. He then worked as a research assistant at the University of Newcastle primarily investigating the diversity of amphibians of the east coast of Australia. Stephen is currently employed at the Australian Museum, Sydney, New South Wales, Australia, as a Technical Officer where he has research interests in amphibian diversity and taxonomy of Australian lizards. (Photographed by Abram Powell).

Dane F. Trembath developed his passion for reptiles while growing up in Kathmandu, Nepal, and Washington D.C., USA. After a B.Sc (Zoology) from James Cook University, Townsville, Queensland, Australia, he completed a Master in Applied Science with the University of Canberra, Australian Capital Territory, Australia, working on Krefft's River Turtle (*Emydura macquarii krefftii*). Dane has been a Research Associate of the Museum and Art Gallery of the Northern Territory, Darwin, Northern Territory, Australia, for 13 y, and he is now also a Research Associate of the Australian Museum, Sydney, New South Wales, Australia. (Photographed by Kathryn Dwyer).

Paul Flemons joined the Australian Museum, Sydney, New South Wales, Australia, in 1998, establishing the spatial analysis capacity of the museum and modeling the spatial distribution of biodiversity. Paul has a particular interest in developing innovative solutions to biodiversity informatics challenges, in particular web-based applications for accessing and analyzing biodiversity collection data. Paul began working in citizen science in 2011 when he established the DigiVol project. In 2015 Paul became the Manager of the Australian Museum Centre for Citizen Science. (Photographed by Paul Flemons).

Adam Woods completed a B.S./Commerce degree from the University of Wollongong, New South Wales, Australia, in 2003. In 2010 he began work in Conservation and Land Management and was drawn to community engagement with Conservation Volunteers Australia. He has a passion for citizen science and its potential to contribute positively to research and conservation and he is currently undertaking a Master's of Philosophy at the University of Wollongong. Adam joined the Australian Museum FrogID project in early 2018. (Photographed by Adam Woods).