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Widespread short-term persistence of frog species after the 2019–2020 bushfires in eastern Australia revealed by citizen science

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Abstract

Fires change ecosystem composition and influence species extinction risk, yet information on the impact of fire on biodiversity is scant. The bushfires in southeastern Australia during the summer of 2019/20 were unprecedented in their extent and intensity, and postfire management decisions have been hindered by a lack of knowledge of the impact of fires on biodiversity. We examine the short-term persistence of frog species across southeastern Australia after these fires using records of calling frogs from the national citizen science project FrogID. We demonstrate widespread short-term persistence of frog species. Sixty-six frog species were detected in the firegrounds before the fire, and within 125 days postfire, 45 of these were detected. All 33 frog species with more than five records that were detected in the months of December–March prefire were detected postfire. While the short-term postfire persistence of so many frog species is a positive result, the population-level and longer-term consequences of the fires remain unknown, as does the ability of frogs to persist with the changing fire regimes predicted as a consequence of global climate change. We illustrate the value of citizen science in collecting large-scale and rapid observations in response to increasing anthropogenically-driven ecological events.

KEYWORDS

amphibians, biodiversity, calling, citizen science, ecology, fire

1 | INTRODUCTION

Fire can cause dramatic changes to ecosystems including increasing species extinction rates (Bond, Woodward, & Midgley, 2005; Fisher, Loneragan, Dixon, Delaney, & Veneklaas, 2009; Gill & Bradstock, 1995). However, there is little information available on the response of most biodiversity, particularly animals, to fire (Dale et al., 2001; Driscoll et al., 2010). This lack of knowledge is a key research gap (Driscoll et al., 2010), hindering our ability to make informed management decisions, and prioritize species for conservation management. Gathering information on species responses to fire is particularly urgent as the size, frequency, and severity of fires are anticipated to increase under climate change (Dale et al., 2001). The need for such data is exemplified by the recent bushfire season of 2019/20 in southeastern Australia.

From September 2019 to January 2020, more than 17 million hectares of forest burnt in Australia, including ~5.8 million hectares of mainly temperate broadleaf forest in New South Wales and Victoria alone (Boer, de Dios, & Bradstock, 2020; Noble, 2020). While bushfires of varying sizes are relatively common in many Australian ecosystems (Moritz et al., 2014), fires of this extent are not (Boer et al., 2016, 2020). By area burnt, this was the largest fire season in southeastern Australia since European occupation (Wintle, Legge, & Woinarski, 2020). Wetter ecosystems (e.g., rainforests) generally burn less frequently, but in 2019/20 up to half of Australia's Gondwana Rainforests World Heritage Area was burnt There is little data on the historical fire frequency of these ecosystems because they do not typically burn (Nolan et al., 2020), highlighting the unprecedented nature of the 2019/20 fires.

The impact of these fires on biodiversity is likely to be dramatic. Although data is sparse, the massive size of the fires suggests that its toll on wildlife may be enormous; with speculations that at least one billion animals may have been killed directly in the fires (Elsworthy, 2020). The indirect toll (e.g., habitat alteration, depletion of resources; Pilliod, Bury, Hyde, Pearl, & Corn, 2003) is unknown. The impact is likely to be particularly severe for species already in decline or of high conservation concern. More empirical data on fire impacts on biodiversity is urgently needed.

Frogs are one of the most threatened groups of vertebrates, as many species have highly restricted ranges, specific microhabitat requirements, and/or have undergone population declines and extirpations in recent decades (IUCN, 2020). At least four of the 240 known native frog species in Australia are extinct and a further 36 are threatened with extinction (Environment Protection and Biodiversity Conservation Act 1999). In addition, frogs are typically not highly vagile, and thus may not be able to flee from fire as easily as other taxa, and because of their semi-permeable skin many frog species are sensitive to desiccation. Given the potential impact of these fires on Australia's frogs, information on their response to fire is urgently needed in order to allow effective conservation management.

Knowledge of frog responses to fire is particularly limited, and much is derived from studies on temperate pond-breeding species in North America (Lowe, Castley, & Hero, 2013). Few studies exist on the impact of fire on Australian frogs, and these have typically indicated that frog species are relatively resilient to fires (Bamford, 1992; Daly & Craven, 2007; Driscoll & Roberts, 1997; Lowe et al., 2013; Potvin et al., 2017; Westgate, Driscoll, & Lindenmayer, 2012; Westgate, MacGregor, Scheele, Driscoll, & Lindenmayer, 2018). However, these studies consider relatively low-intensity fires, a limited number of species and relatively small geographic areas.

Current species prioritization efforts in the aftermath of the 2019/20 fires are hindered by a lack of data on the overall vulnerability of Australia's frogs to fire as well as species-specific responses. In the aftermath of the fires, assessments of the likely impacts of fire on some species, and subsequent prioritization efforts, were based on best guesses rather than empirical evidence (Ward et al., 2020). This data gap exists due to logistical challenges involved in collecting postfire data in a timely fashion across a wide area. Citizen science offers a new and powerful approach to this problem, capable of rapidly responding to catastrophic events such as fires across a large spatial scale (Kirchhoff et al., 2020). This is particularly true for ongoing citizen science projects that have likely collected "before" data, providing the necessary temporal comparison with "after" data following catastrophic events.

The national citizen science project, FrogID (Rowley et al., 2019), provides an unparalleled opportunity to further our understanding of the impacts of fire on Australian frogs. Using the FrogID dataset, we examine the short-term persistence of frog species across southeastern Australia after the 2019/20 bushfires.

2 | METHODS

2.1 | FrogID dataset

FrogID is a national citizen science project launched in November 2017 (Rowley et al., 2019). Participants submit 20–60 s audio recordings of calling frogs using a smartphone app, and the app adds associated metadata (time, date, latitude, longitude, and an estimate of precision of geographic location) to each submission. Along a spectrum of control in citizen science projects (Welvaert & Caley, 2016), ranging from structured (i.e., trained participants following dedicated protocols) to unstructured (i.e., incidental data collection with little to no training by participants), FrogID is largely unstructured, allowing participants to submit observations at locations and times of their choosing. Once FrogID users submit recordings, the cloud-based FrogID Content Management System (CMS) receives the recordings and a team of experts then identifies all frog species heard calling. As frogs call almost exclusively from breeding sites, localities of calling frogs are typically breeding habitats (Rowley et al., 2019; Rowley & Callaghan, 2020).

We used FrogID data validated from 10th November 2017 to April 13, 2020, contributed by 12,377 volunteer citizen scientists from 65,499 unique locations (i.e., latitude/longitude combinations). We excluded any submissions that had a geolocation accuracy >3 km, because these represent submissions which indicated the app was unsure of the location (Rowley et al., 2019), resulting in 169,575 frog records across Australia.

2.2 | DEA hotspot data

We used two different sources of data on the 2019/20 Australian fires. First, we used the National Indicative Aggregated Fire Extent map (downloaded from: http://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B9ACDCB09-0364-4FE8-9459-2A56C792C743%7D) to delineate the extent of the fires throughout the region. But because this product does not provide information on the timing and intensity of the fires, we also downloaded hotspot data on fires from Digital Earth Australia (DEA) Hotspots (https://hotspots.dea.ga.gov.au/). These data are part of a national bushfire monitoring system which uses satellite sensors to provide governments with the spectral signature of fire (i.e., hotspots). We downloaded all DEA hotspot data from within a minimum bounding box which was bounded by −24° and −44° latitude and 134° and 154° longitude; and data were downloaded from the time period November 1, 2019 to February 12, 2020.

Due to the vagaries of winds, temperatures and the distribution of fuels, bushfires burn a complex mosaic of high intensity, low intensity, and unburned patches within the firegrounds (Collins, Bennett, Leonard, & Penman, 2019). This, together with the location accuracy of some FrogID recordings, makes precisely characterizing the fire intensity associated with each frog record difficult. That said, this set of fire events did have certain periods when high winds and temperature meant that the fire front burned with high intensity through large areas. Yet at other times and in other areas, low winds and temperatures led to a much lower intensity fire, and satellite measurements provide, albeit with some uncertainty, the intensity of a fire front at a given place and time. Typically, the fire-front is the hottest close to the onset of the fire followed by a lower temperature phase of continued burning. As the fire front passed, it was recorded by the national bushfire monitoring system as a series of "hotspots" based on spectral data from multiple satellites. One limitation to these data is that while the data product uses multiple satellites, there are still gaps in space and time associated with their particular orbital paths, implying that the time estimates for the fire front could be late by up to 8–12 hr.

We matched each FrogID record with the best available data on the nature of the fire front as it passed by each location by combining our frog records with DEA hotspot data (https://hotspots.dea.ga.gov.au/) by placing a 0.005° buffer around each record and found the highest temperature hotspot within that buffer; this assumes that the highest temperature record is the one closest in time to the moment the fire front passed by each location. Because the timing of the satellite passes and firefront are unlikely to line up exactly, the temperature represents a general characterization of the fire front intensity in the area and not necessarily the temperature experienced by the frog *in situ*. The relatively coarse scale of the hotspot data does not allow the detection of small patches of unburnt habitat, which are typical within the fire footprint (Wintle et al., 2020). However, unburnt patches are more frequent in low-intensity fires compared to high-intensity fires, and, at least in some regions, the 2019/20 fires appeared to have burnt the landscape so thoroughly that areas that have previously acted as fire refuges (e.g., gullies and riparian habitat) were also burnt (Wintle et al., 2020). We then calculated the number of prefire records of frog species (including across multiple years) and postfire (only those recordings following the DEA hotspot data). In our comparison of pre- and postburn species records, we filtered FrogID data to only include records between 1 December and 31 March of each year, limiting our comparison to species with a breeding season spanning postfire months ("summer breeding" frog species). This gave 4 months of postfire data (December 2019–March 2020) and up to 10 cumulative months of prefire data (December 2017–March 2018, December 2018–March 2019, and December 2019–January 2020).

2.3 | Frog species categories

In order to determine if there were trends in the short-term persistence of frog species after fire, we assigned each frog species to ecological group (stream associated, permanent water associated, temporary water associated, both temporary and ephemeral water associated, moist bog or soak associated and terrestrial breeder; Murray, Rosauer, McCallum, & Skerratt, 2011) and lifestyle mode (arboreal, terrestrial, or burrowing; Young, Christian, Donnellan, Tracy, & Parry, 2005; Rowley, pers. obs.).

3 | RESULTS

The FrogID dataset included a total of 3,387 observations of 69 frog species in the study area (Figure 1a; Appendix S1). Of these, 2,655 observations at 1,091 unique locations (i.e., latitude/longitude combinations) of 66 species were

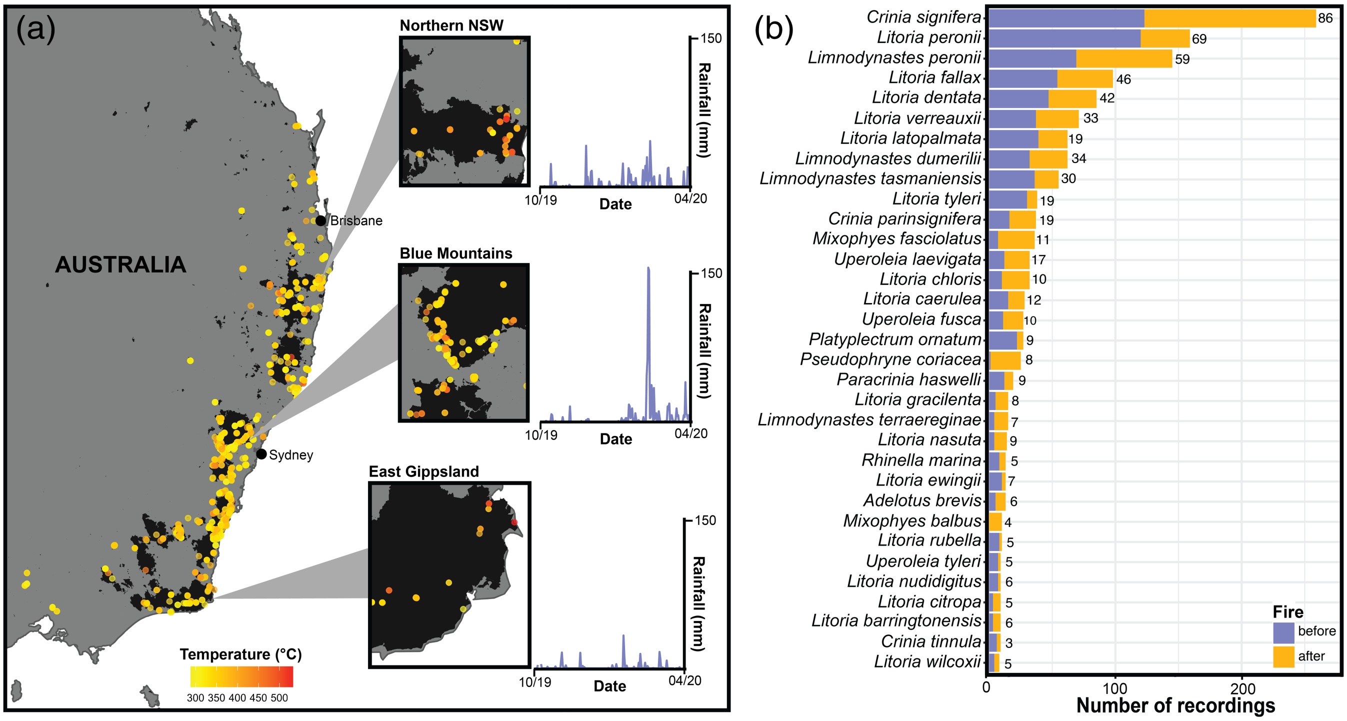

FIGURE 1 (a) Map of the study area, showing the National Indicative Aggregated Fire Extent Dataset (black), and the temperature of the DEA hotspots with FrogID records (both pre- and postfire). Insets represent three representative areas plus daily rainfall records from these areas (Glen Innes, Blackheath and Malacoota, obtained from the Bureau of Meteorology, http://www.bom.gov.au). (b) The number of recordings before and after the fires in areas burnt in the 2019/2020 fires in eastern Australia for the 33 species of summer-breeding frogs with more than five FrogID records. Numbers at the end of each bar represents the number of DEA hotspot buffers (=sites) for that species

made prefire and 632 observations at 295 unique locations of 45 species were made postfire. The location of pre- and postfire records were often clustered together (Appendix S2), but only 20 unique locations (exact latitude/longitude) were sampled both pre- and postfire.

The most often recorded frog species in the FrogID database in burnt areas postfire were common species distributed throughout large areas of eastern Australia and of low conservation concern (Figure 1b), however rare and threatened species were also documented calling postfire. Five species listed as threatened (Biodiversity Conservation Act 2016) were recorded postfire (*Crinia tinnula*, *Mixophyes balbus*, *Mixophyes fleayi*, *Mixophyes iteratus*, and *Philoria kundagungan*), four of which were among the 16 frog species identified as being the highest priority for management intervention postfire (Legge et al., 2020; *Mixophyes balbus*, *Mixophyes fleayi*, *Mixophyes iteratus*, and *Philoria kundagungan*). Surprisingly given the short time window and the high degree of disturbance there were no "missing" frog species, species that would be expected to have been detected postfire but were not. In other words, all 33 summer-breeding frog species (recorded between December and March since November 2017) with more than five FrogID records detected prefire were detected postfire (Figure 1b).

Some of the post fire observations of calling frogs were from sites that burned at high temperatures: the estimated temperature of fires varied from ~290 to 530°C. Several frog species were recorded postburn at high temperature burning sites, with *Pseudophryne coriacea*, *Crinia signifera*, and *Litoria verreauxii* recorded post fire at sites where temperatures were estimated to be >500°C (Appendix S3). The number of days between the fire and frog calling activity varied, with three species detected calling after 1 day, eight species within 1 week, and 14 species within 1 month (Figure 2). Frog species detected postfire were taxonomically diverse, with representative species record postfire in all frog families present in the region. There were no clear correlations in the ecological group or lifestyle of species that were detected postfire (Figure 2).

4 | DISCUSSION

Sampling by citizen scientists reveals widespread short-term persistence of frog species across southeastern Australia after the 2019/20 bushfires, with 45 frog species detected within 125 days postfire. Importantly, all 33 species of summer-breeding frogs with more than five

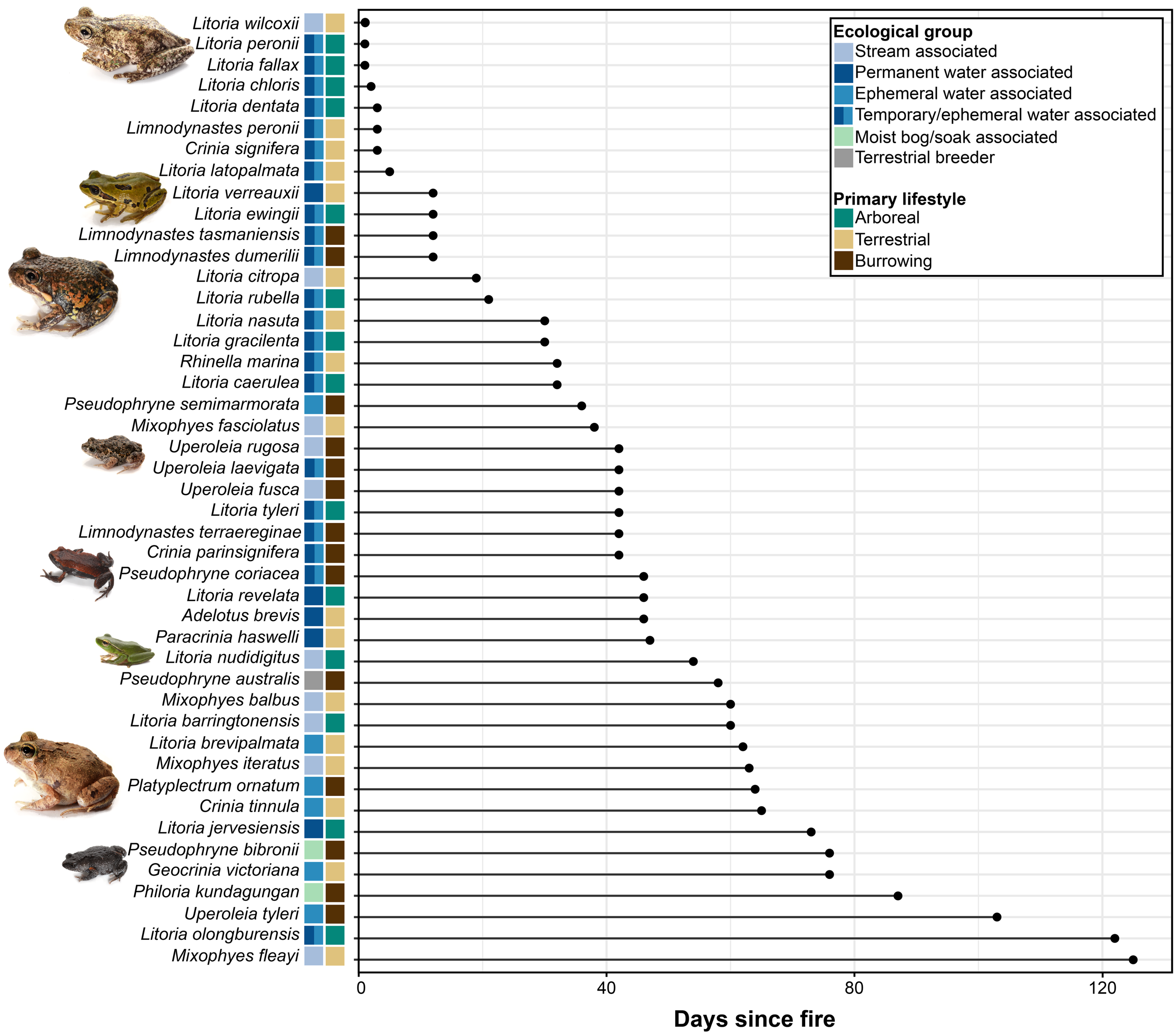

FIGURE 2 Minimum time to a recorded call in burnt areas post 2019/2020 fires for the 45 species with calls recorded postfire. Ecological group and primary lifestyle are indicated for each species

records detected in now burnt areas prefire (i.e., those species that were likely to have been detected via FrogID if present) were also detected postfire. All families of Australian frogs present in the area were detected postfire, as well as species across a wide range of ecological groups and lifestyles. While widespread frog species of low conservation concern were most commonly detected postfire, rare and threatened frog species were also documented, including four of the 16 the species identified as priority for management intervention postfire (Legge et al., 2020). Some of the priority species not detected are restricted to small areas of remote habitats unlikely to be sampled by citizen scientists (i.e., *Pseudophryne corroboree*, *Pseudophryne pengilleyi*), while others breed primarily in months other than those sampled postfire (i.e., *Philoria pughi*, *Litoria subglandulosa*), and may be detected in future FrogID recordings.

The viability of populations through a fire event has several stages, which in aggregate lead to the long-term viability of populations: first is short-term persistence through a fire, the second is successful breeding postfire, and the third is the survival of the adults and/or juveniles in the postfire environment. Data collected with different methods and timing inform an understanding of these stages and can together build a picture of the longterm viability of frog populations through fire. The method used here, the detection of postfire calling by frog species, is evidence of short-term persistence and attempted breeding activity, but this approach cannot inform estimates of breeding success or recruitment, which are necessary for a complete picture of the effect of the fire on population dynamics. Moreover, the persistence of a species in one area may not indicate its persistence in other areas, as the effect of fire on frog occurrence is likely to vary with factors such as vegetation type, fire history, and connectivity (Pilliod et al., 2003; Westgate et al., 2018). The more subtle impacts of fire, including increasing vulnerability to extinction from future threats (e.g., Potvin et al., 2017), will not be immediately evident.

Presumably, most frogs detected in burnt areas postfire were able to seek refuge from the intense heat of the fire front in waterbodies, underground, or under objects such as rocks and logs where the thermal inertia of their surroundings keeps the fire's heat from being lethal (e.g., Bamford, 1992; Friend, 1993). However, it is possible that some frog species detected calling did not survive fires in situ, but recolonized burnt areas postfire from nearby refugia or outside the fire zone. Indeed, frogs within the fire footprint may have persisted in patches of unburnt habitat of various sizes, which are common, particularly in sheltered, wetter microhabitats where fires tend to burn at lower intensity (Wintle et al., 2020). Regardless, several frog species were calling almost immediately postfire (within a few days; Figure 2), and so we assume that at least some individuals survived the fires close by to where they were subsequently heard. In addition, due to the reliance of many frog species on rainfall to call, the extremely dry conditions across much of eastern Australia at the time of the fires (Boer et al., 2020) means that the first opportunity for many species to occur was in February 2020, when significant rainfall occurred across the region (Figure 1, Appendix S1). Had rainfall occurred earlier, it is likely that many frog species would have been detected earlier.

The full impacts of the 2019/20 fires on Australian frogs will not be evident for some time. Likely compounded by the severe drought in southeastern Australia prior to and during the fires, along with other stressors including disease and habitat modification (Ward et al., 2020), the ability of Australian frogs to recover from this event is unclear. Species with small geographic ranges, especially rainforest-dependent species are of particular concern. Although the FrogID project is highly effective in targeting range-restricted, threatened species when championed by local communities (i.e., *Crina sloanei*; Rowley et al., 2019), the FrogID dataset contains few records for a number of range-restricted species of high conservation concern. This is particularly the case for species located in remote or difficult to access sites (Callaghan et al., 2020). As such, targeted structured surveys by professionals will be needed to monitor populations of these species.

These results present a snapshot across the fire zone in the immediate postfire period. Much remains unknown, but continued data collection by citizen scientists across the firegrounds will offer effective monitoring for the coming years. Repeated fires in future years in certain areas may also have the effect of pushing many populations to unrecoverable levels, and this multifire effect will only be detectable with continued sampling at scale. A dynamic, interactive approach with the citizen scientists (e.g., Callaghan, Poore, Major, Rowley, & Cornwell, 2019), will ultimately help to direct the immense citizen science effort to better capitalize on the value of citizen scientists to quantify species' responses to stochastic events. We suggest that citizen science data could be made even more valuable by targeting (a) previously well-sampled areas, (b) areas that experienced high intensity fire, and/or (c) rare and threatened ecological communities.

Citizen science has the capacity not only to collect large datasets across a broad geographic area, but to generate data rapidly, allowing a timely response to help understand the impact of stochastic events such as landslides, floods and severe weather (Hicks et al., 2019). The 2019/20 bushfires were of a scale too large for a rapid response to using conventional biodiversity monitoring methods (Kirchhoff et al., 2020). Much of the area burnt was on private properties, and movement restrictions due to COVID-19 in the months after fires presented further logistical problems for professional surveys across the fire grounds. Together with more traditional biodiversity surveys by professionals, citizen science projects such as FrogID present an opportunity to gather the information that we need to rapidly understand and respond to the impact of stochastic events such as fires on our biodiversity.

Our findings support the growing global literature that many frog species across a range of geographic, taxonomic, and ecological groups are capable of persisting through fire (Bamford, 1992; Lowe et al., 2013; Pilliod et al., 2003; Potvin et al., 2017; Westgate et al., 2012, 2018). While we report only on the short-term persistence of frogs after fires, we demonstrate that citizen science can be a powerful tool in rapidly understanding how biodiversity responds to catastrophic events such as bushfires.

Understanding the effects of fire on population viability in frogs is a difficult task, but continued use of FrogID, combined with targeted scientific surveys, will allow a greater understanding of the impact of the fires on these frog species in the immediate aftermath (as shown here) and further into the future. There is an urgent need to understand the impact of fires on Australia's frogs, particularly given the more frequent and more severe fires predicted as a consequence of global climate change (Moritz et al., 2012; Williams et al., 2009), and when combined with drought, disease and other potential threats. Citizen science data will form a key resource in this effort.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Jodi J. L. Rowley, Corey T. Callaghan, and William K. Cornwell contributed to concept, analysis, writing, and revision of the manuscript.

DATA AVAILABILITY STATEMENT

All frog location data cannot be made Open Access due to data sensitivity, but most frog locality data is made publicly available on an annual basis (Rowley & Callaghan, 2020). Further data can be requested from the FrogID project or the Corresponding Author.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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