Northern Corroboree Frog: current status and recovery actions

Murray Evans

Research Report
Conservation Research
February 2019

Research Report Series

Northern Corroboree Frog:
current status and recovery actions

Murray Evans

Conservation Research
Environment, Planning and Sustainable Development Directorate

February 2019

© Australian Capital Territory, Canberra, 2019

Information contained in this publication may be copied or reproduced for study, research, information or educational purposes, subject to appropriate referencing of the source.

This document should be cited as:
Evans M. 2019. Northern Corroboree Frog current status and recovery actions. Unpublished report, Research Report Series. Environment, Planning and Sustainable Development Directorate. ACT Government, Canberra.

ACT Government website
www.environment.act.gov.au
Telephone: Access Canberra 13 22 81

Disclaimer
The views and opinions expressed in this report are those of the author and do not necessarily represent the views, opinions or policy of funding bodies or participating member agencies or organisations.

Front cover: Juvenile Northern Corroboree Frog bred at Tidbinbilla Nature Reserve. Murray Evans.

Contents

Summary

This report describes the current conservation status of the Northern Corroboree Frog in the Australian Capital Territory and provides an overview of recovery actions taken to date. The report also provides guidance on future directions for the Northern Corroboree Frog recovery program in the ACT.

Northern Corroboree Frogs (*Pseudophryne corroboree*) and Southern Corroboree Frogs (*P. corroboree*) have restricted distributions in the higher elevation areas of the Australian Alps, and occur only where suitable breeding habitat (sphagnum moss bogs and other wet areas) is present. Both species underwent catastrophic population declines in the 1980s and the decline is ongoing. The main cause of the decline is the Amphibian Chytrid Fungus, which first appeared in Australia in the 1970s and is now widespread.

Key breeding sites for the Northern Corroboree Frog in the ACT have been monitored since the mid-1990s, and in 2017 an additional 35 sites with historical breeding records were surveyed. In the ACT, of the 40 sites where Northern Corroboree Frogs once occurred in the ACT, the species is now known to occur only at five sites, which includes two sites where the species has been reintroduced (from captive-bred individuals) and three other small sites that contain the few remaining wild individuals. The once very common Northern Corroboree Frog is now rare in the ACT, and without continuing recovery efforts the species is almost certain to become extinct in the ACT.

In 2003 a captive insurance population of Northern Corroboree Frogs was established at Tidbinbilla Nature Reserve (NR), and in 2010 a second smaller captive population was established at Healesville Sanctuary in Victoria from captive-bred progeny from Tidbinbilla NR. Since 2011 Corroboree Frogs have been experimentally released each year to two sites in Namadgi National Park with the aim of establishing wild populations to facilitate natural disease resistance to Chytrid Fungus.

Monitoring of calling males indicates the reintroductions have established a breeding population of around 40 individuals across the two sites. Some of these individuals have successfully bred and the fertile eggs have been brought back to the captive population at Tidbinbilla to be raised. Population modelling suggests a strategy of releasing frogs that are two or three years older will boost the size of wild breeding populations. Raising Corroboree Frogs in outdoor enclosures at Tidbinbilla is being trialled as a cost-effective method to expand the capacity of the Corroboree Frog facility, which will provide space for additional frogs to be raised to older ages for release. The National Recovery Team for Corroboree Frogs recommends captive insurance populations be maintained whilst the species remains under the threat of extinction in the wild and there is some chance of recovery for the species.

1 Purpose

This report has three aims. Firstly, to describe the current (2018) conservation status of the Northern Corroboree Frog in the ACT, including the results of a broad-scale survey of historic breeding sites undertaken in 2017. Secondly, to provide an overview of the ACT recovery program for the species and actions taken to date, including establishment of a captive insurance population at Tidbinbilla Nature Reserve in 2003, experimental releases to the wild since 2011, and analyses of these releases using population modelling. Lastly, to provide guidance for future directions for the recovery program. The report also provides brief background on the distribution, ecology, and decline of the species in the wild.

2 Background

Distribution

Corroboree Frogs have a restricted distribution in the higher elevation areas of the Australian Alps where they occur in montane and sub-alpine woodlands and associated wet seepage areas. Since 1996 two species of Corroboree Frog have been recognised (Osborne et. al. 1996); the Southern Corroboree Frog *Pseudophryne corroboree*, which occurs in Kosciusko National Park, and the Northern Corroboree Frog *P. pengilleyi*, which occurs in the Brindabella Range in the ACT and in the adjacent Fiery Ranges and Bogong Mountain areas of NSW (Figure 1).

In the ACT, the Northern Corroboree Frog occurs as two populations, a higher elevation southern Brindabella population and a lower elevation northern Brindabella population (ACT Government 2011). The southern Brindabella population is found montane and subalpine zones (between about 1400 and 1850 m) along the Brindabella Range from Ginini Flats to about the summit of Mt Bimberi, though historical records include lower areas (down to 740 m). This southern Brindabella population occurs only within Namadgi National Park (ACT) and to a lesser extent in the adjacent Bimberi Nature Reserve in NSW, with the largest numbers of frogs historically occurring at Ginini Flats and Snowy Flats in the ACT. The northern Brindabella population occurs in the northern extent of the Brindabella Range from about Bushrangers Creek in the ACT northwards to near California Flats in NSW.

Population decline

Observations of Southern Corroboree Frogs and Northern Corroboree Frogs in the 1960s and 1970s indicate these species were abundant in suitable habitat within their respective distributions (Pengilley 1966, 1992; Osborne 1989; Osborne et al. 1999). However, both species underwent widespread and severe declines that commenced sometime during the early to mid-1980s (Osborne 1989; Hunter et al. 1999; Osborne et al 1999; Hunter et al. 2010). Almost all populations of Southern Corroboree Frogs have become extirpated and the number of adult Southern Corroboree Frogs remaining in the wild is less than 50 (Hunter et al. 2018).

In the ACT region, some historical breeding aggregations of Northern Corroboree Frogs were reported to be large (such as those at Ginini Flats and Snowy Flats) consisting of many hundreds of individuals (Pengilley 1966; Osborne 1988). Populations of Northern Corroboree Frogs at Ginini Flats West have been monitored regularly since the mid-1980s and other sites in the ACT have been monitored since the mid-1990s (Osborne 1989; Osborne et al. 1999; M. Evans ACT Government unpubl. data) (see section on monitoring of key breeding sites). The monitoring results indicate that Northern Corroboree Frog populations underwent a catastrophic decline in the 1980s and the decline is ongoing.

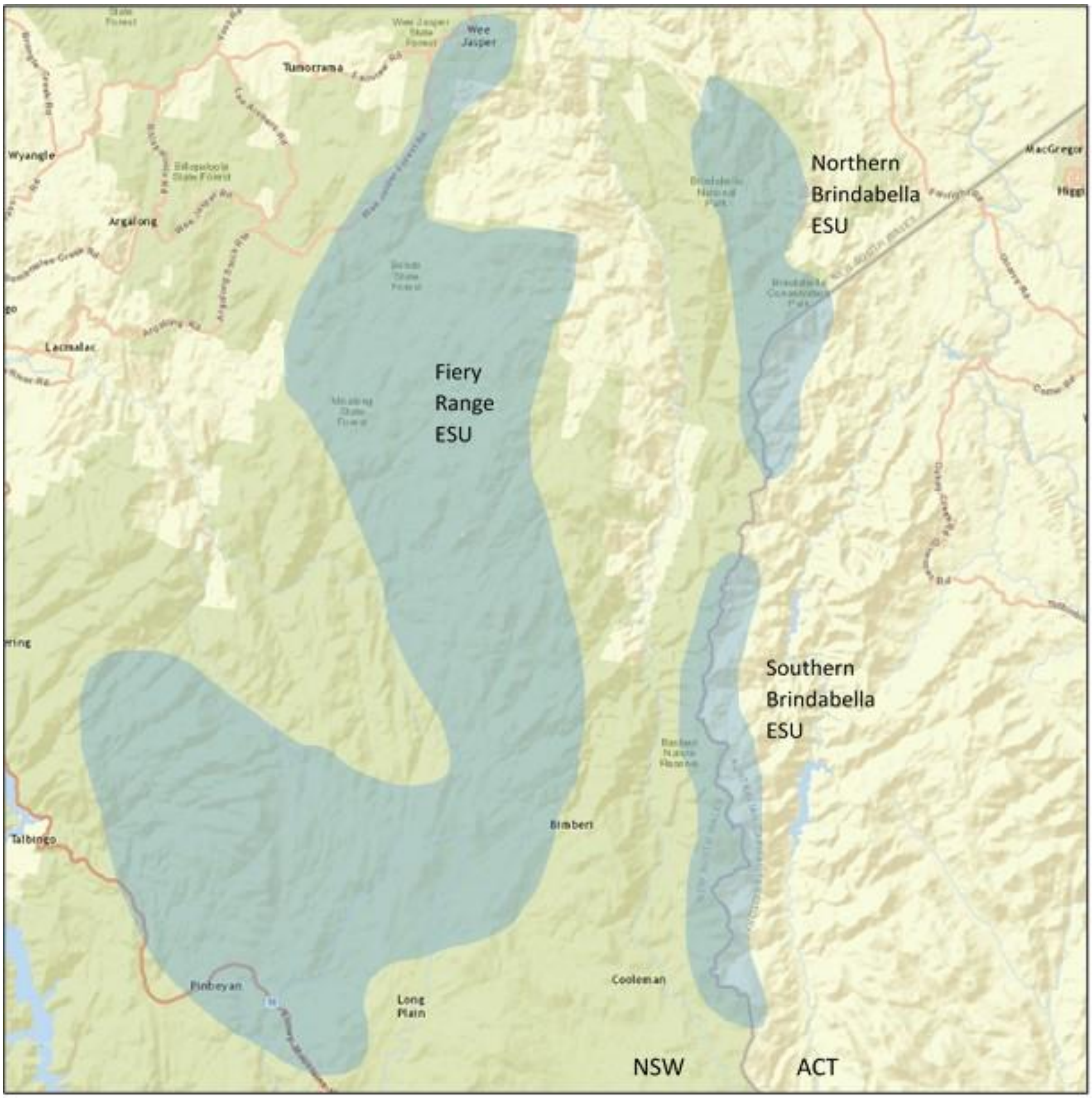

Figure 1. Map showing ACT/NSW border and historic distribution of the Northern Corroboree Frog (dark shading).

At Ginini Flats West there was estimated to be at least 500 male Northern Corroboree Frogs calling in 1986; three years later the number had dropped to about 50 calling males and in 1992 there were estimated to be about 25 calling males (Osborne et al. 1999; ACT Government unpublished data)

(Figure 7). The number of calling males at Ginini Flats West has fluctuated in subsequent years (for example, about 50 calling males in 1993, about 10 in 1997 and about 26 in 1999) but the overall trend has been a decline to one calling male in 2012 and no calling males in 2014 (no monitoring was undertaken in 2013). The main cause of decline of Corroboree Frog populations is the Amphibian Chytrid Fungus *Batrachochytrium dendrobatidis* (see section on Chytrid Fungus). A small increase in numbers of calling males at Ginini Flats West since 2015 has followed annual releases of captive-bred Northern Corroboree Frogs from Tidbinbilla Nature Reserve, and on occasion captive-bred individuals from Healesville Sanctuary, to this site (see section on Captive Breeding and Release).

Genetics of wild populations

Based on analysis of mitochondrial DNA, Morgan et al. (2008) identified three Evolutionary Significant Units (ESU's) (i.e. genetically distinct entities) for Northern Corroboree Frogs:

- NSW Fiery Ranges,
- NSW/ACT Northern Brindabellas, and
- ACT Southern Brindabellas.

These three ESUs are each represented by populations of frogs that are genetically different (Osborne 1989; Osborne and Norman 1991; Morgan et. al. 2008). The ACT Southern Brindabella population occurs in cooler, higher elevation areas such as Ginini Flats, whereas the other two populations occur at lower elevations. The genetic differences between the Northern and Southern Brindabella populations are less than between these two populations and the Fiery Range population. This suggests that historically the species occurred in the intermediate areas between the Brindabella Range populations, facilitating gene flow between them.

The genetic diversity of both species of Corroboree Frogs is still reasonably high, the result of a decline that is only recent (Morgan et al. 2008). However, genetic diversity will continue to be eroded whilst populations remain small (Lindenmayer and Burgman 2005). Indeed, signatures of genetic bottleneck (i.e. the genetic effects of small population size) were detected from some breeding sites, including Ginini Flats in the Southern Brindabella ESU. The Southern Brindabella ESU also had the lowest genetic diversity of the three Northern Corroboree Frog ESUs and was also lower than the single ESU for the Southern Corroboree Frog (Morgan et al. 2008).

Biology and ecology

Corroboree Frogs use two distinct types of habitat; a summer breeding habitat and an 'over-wintering' habitat (Pengilley 1966; Osborne 1988; Osborne 1990; Hunter et al. 2009a). The frogs spend the cold winters sheltering beneath leaf litter and logs in montane or sub-alpine woodlands or tall moist heath. During January the frogs move out of the woodlands and heath and into nearby wet seepage areas such as sphagnum moss bogs. In these summer breeding areas the males call to females from terrestrial nest sites within the moss or other damp vegetation located next to pools or areas that might later become pools. The peak of breeding season calling is between late January and late February (Pengilley 1971, Evans pers. obs). The males have an advertisement call, a courtship call and a threat call (Pengilley 1971).

Figure 2. Woodland adjacent to Ginini Flats East (E. Beaton, ACT Government)

Males use the advertisement call and courtship call to attract females, whereas the threat call is directed at other males. The intensity of the advertisement varies depending on the weather, with more calling occurring during warmer overcast conditions, and during late afternoon (Pengilley 1971; Osborne 1989).

After laying around 25 eggs during the summer breeding season the females return to the adjacent woodlands or heath. Males continue to call until early Autumn, presumably to continue attracting females because males can accumulate multiple clutches in their nest site. In early Autumn the males move back to the adjacent woodlands. Osborne (1988 and unpublished) found that following breeding, adult Northern Corroboree Frogs are capable of moving over 300 metres into the surrounding woodland.

Females lay relatively few (around 16 to 38) eggs (Pengilley 1973; Evans pers obs.) for an amphibian. The eggs develop to an advanced stage in the terrestrial nest and then remain in a suspended state (diapause) until rainfall or snowmelt in late autumn or early spring floods the nest, at which point the eggs hatch and the tadpoles move into the pool. Tadpoles that hatch before winter exhibit little growth over winter, with steady growth occurring during the warmer spring months. Metamorphosis occurs in late spring or summer (Hunter et al. 1999; Hunter and Osborne 2000). The pre-metamorphic period is critical for reproductive success, because eggs and tadpoles are vulnerable to desiccation and pool-drying at this time (Hunter 2000). Hunter (2000, 2001) found average survivorship from egg to metamorphosis for Southern Corroboree Frogs to be 20 percent during favourable (wet) breeding seasons (absence of early pool drying), whereas early pool drying (i.e. drying of the pools before tadpoles reach metamorphosis) during dry breeding seasons typically caused complete failure of recruitment to metamorphosis for that year.

Recently metamorphosed frogs probably remain in moist vegetation near the pools for several months, feeding on a range of small invertebrates including ants (Pengilley 1966, 1973). As the frogs grow larger they move out of the breeding habitat into the fringing heath and woodland where they probably remain until breeding age (Pengilley 1966, 1992). Hunter (2000) used skeletochronology to determine when Southern Corroboree Frogs reach breeding age, which was found to be four years post-metamorphosis for males with a small proportion attaining sexual maturity in three years. Using this technique, the oldest wild individuals were found to be nine years post-metamorphosis (Hunter 2000). The proportion of adult (breeding age) male Southern Corroboree Frogs surviving each year was determined to be between 50 and 60 percent (Hunter 2000). Because juvenile frogs don’t call they are difficult to locate and study, and hence information is lacking on the survivorship of Corroboree Frogs from metamorphosis to breeding age. Females do not have a breeding call, nor do they remain in the nest, and so they are difficult to study using techniques such as skeletochronology, though it is likely that majority of females take four or five years post-metamorphosis to attain sexual maturity (OEH 2012).

Figure 3. Typical ephemeral pool used for breeding by Northern Corroboree Frogs in Namadgi National Park.

3 Threats

Predators and Parasites

Despite a number of research and monitoring projects on Corroboree Frogs, including post-graduate studies by R. Pengilley, W. Osborne and D. Hunter, and ongoing monitoring by the NSW and ACT Governments, no evidence of predation on Corroboree Frogs has been reported. The tadpoles of many frog species are subject to predation from fish and invertebrates (Heyer et al. 1975; Caldwell et al. 1983; Duellman and Trueb 1986), though it is unlikely that such predation is a significant source of mortality in Corroboree Frogs because these predators are scarce in pools used by Corroboree Frogs. Potential predators of terrestrial frog stages (such as herons and snakes) are also unlikely to be a significant source of mortality for Corroboree Frog populations because these predators are very uncommon at high montane and subalpine altitudes (Green and Osborne 1994). It is unknown whether crayfish (*Euastacus reiki*) that occur in high elevation sphagnum moss bogs are predators of any life stages of Corroboree Frogs.

Protozoans, helminths, leeches, mites and the larvae of flies are known parasites of frogs (Tyler 1976; Duellman and Trueb 1986). In Australia, *Pseudophryne* spp. are parasitised by *Batrachomyia* (frog flies), protocephalid cestodes and oxyuroid nematodes (Pengilley 1966; Tyler 1989), though infestation rates in Corroboree Frogs are apparently generally low (Pengilley 1966; W. Osborne, unpublished data). Whilst many parasites are not lethal to their hosts, sporozoans have been observed to cause high mortality in adults and tadpoles in other countries (Duellman and Trueb

1986). *Tetrahymena* ciliates, which are free living protozoa (micro-organisms) in freshwater ponds, have been found to cause mortality of Northern Corroboree Frog eggs and tadpoles under certain conditions in captivity (M. Evans unpublished data).

Chytrid Fungus

The main cause of decline of Corroboree Frog populations is the Amphibian Chytrid Fungus *Batrachochytrium dendrobatidis* (Hunter et al. 2010; Gillespie et al. 2015; Scheele et al. 2016), which first appeared in Australia in the 1970s and is now widespread (Murray et al. 2010). The disease caused by the fungus (Chytridiomycosis) was first observed in Australia in dead and dying frogs in Queensland in 1993, but the causal agent (Amphibian Chytrid Fungus) was not identified until 1998 (Berger et al. 1998, 2009).

Chytrid fungi typically live in water or soil, and some are parasites of plants and insects. The Amphibian Chytrid Fungus exists as either mobile (swimming) zoospores, or sessile zoosporangium (capsule embedded in the frog's skin that produce zoospores). Only the Amphibian Chytrid Fungus is known to infect vertebrate species. Frog and tadpole stages contract the disease when their skin comes into contact with water that contains spores from infected animals. The fungus invades the surface layers of the frog's skin, causing damage to the keratin layer and other systemic effects in frogs. The fungus is highly infectious to amphibians and has resulted in declines and extinctions of frogs around the world, mostly in cool, high, mountainous areas. In Australia it has caused the extinction of at least four species and the dramatic decline of at least 10 species (Murray et al. 2010). In some frog populations, the disease causes 100 per cent mortality, while in other populations, it causes very few deaths. Some amphibian species appear to be highly susceptible and die quickly, whilst others seem to be less susceptible (Kriger and Hero, 2006). With antifungal and supportive treatment, infected adult frogs and tadpoles in captive populations can fully recover from the disease.

Many species in the wild remain at lower abundance and smaller distributions than prior to the disease epidemic, some are continuing to decline, and significant mortality from chytridiomycosis is ongoing even decades after introduction (McDonald and Alford 1999; Murray et al. 2009; Hunter et al. 2010). Currently there are no proven methods to control the disease in the wild. Mass declines of frog species occurred during the 1980s and 1990s, and declines are still continuing in some species such as Corroboree Frogs (Osborne et al. 2000; Hunter et al. 2010; Gillespie et al. 2015; Scheele et al. 2016).

A key reservoir (or host) species in the Australian Alps (where Corroboree Frogs occur) is the Common Eastern Froglet (*Crinia signifera*), a widespread abundant species that often carries high levels of infection by Chytrid Fungus (Hunter et al. 2009b; Brannelly et al. 2017) and is a source of infection and reinfection for wild Corroboree Frogs.

Other Threats

In addition to the devastating impact of Amphibian Chytrid Fungus on Northern Corroboree Frogs, other threats include mortality of eggs or tadpoles due to desiccation of pools during dry years (Figure 4), alteration of habitat from severe fire, and damage to habitat from introduced animals. For small populations the effects of threats becomes magnified (Caughley and Gunn 1996) and include additional factors such as genetic problems (random genetic drift, inbreeding and loss of genetic diversity).

Figure 4. Early pool drying before metamorphosis can result in loss of all tadpoles and hence low or no breeding success for the year.

Reliable autumn precipitation is critical to the hatching of eggs and over-winter survival of the tadpoles. It appears that if the nests are not submerged during this period, then the eggs either do not hatch, or hatch prematurely in the nest site with the tadpoles becoming stranded in the dry vegetation surrounding the nest (Hunter 2000). The tadpole life stage is also critical, because even if the tadpoles move into the pools their slow development to metamorphosis means they are vulnerable to pool-drying. It is likely that Chytrid Fungus and drought act synergistically, so that frog populations that are experiencing high mortality due to Chytrid Fungus are more susceptible to drought, and/or do not recover following drought (Scheele et al. 2016).

Alteration of quality or quantity of habitat (particularly breeding habitat) it likely to be a major factor affecting recruitment and survivorship of Corroboree Frogs, and hence population size. The 2003 wildfires that burnt large areas of Namadgi and Kosciusko national parks had a profound impact on the sphagnum moss bogs and other wetland areas that are used by Corroboree Frogs. The fires also resulted in direct mortality of what appeared to be a substantial proportion of the frog population at these sites. However, the effects of such infrequent fires are relatively short term, as the habitat began recovering over the subsequent few years following the 2003 fire, and within four years

Corroboree Frogs in the ACT were again using previously severely burnt areas that had regenerated (Evans pers. obs.). However, even the short-term effects of fire can be catastrophic for species that are stressed by other factors (eg. drought, disease) or that have declined to small isolated populations that are on the edge of viability.

4 Monitoring of key breeding sites

Monitoring of numbers of calling males has been undertaken by the ACT Government (Conservation Research section) at Ginini Flats West (MGA 94: 660696, 6067932) since 1986, and at Ginini lats East (661543, 6067657), Snowy Flats (661811, 6063323) and Cheyenne Flats (661771, 6066539) since 1996, and at Hanging Flat West (662554, 6061740) since 2004 (Figure 8). These five monitoring sites and other sites had been previously surveyed on an ad-hoc basis.

Monitoring methods

Monitoring of the abundance of both species of Corroboree Frogs involves counting the number of calling males at breeding sites during the peak calling period of the summer breeding season. Breeding sites are contiguous areas of peat bog, fen, wet tussock grassland or other wet seepage areas that typically contain a number of pools, or potential pools (depressions that usually have a mud or sediment base and that may at other times contain water). Most pools are small (< 3 m diameter) but some are large (up to 8 m diameter). Pools are usually ephemeral, filling with water for part of the year due to rainfall or snowmelt, though some pools may be present all year round except during low rainfall years. Larger breeding sites in the ACT tend to have a small stream flowing through the bogs or along their edge, though these running streams are not suitable breeding habitat for corroboree frogs, which use pools where the water is still or only very slowly flowing. In the summer breeding season males congregate in the damp vegetation at the edges of pools, or potential pools.

Surveys for the Northern Corroboree Frog in the ACT have been undertaken in the first two weeks of February (for consistency), which is around the peak calling period of the summer breeding season (January to March). The number and location of calling males at sites is determined using the shout-response technique (Osborne 1989), which involves a person shouting loudly at a potential breeding pool, to which male corroboree frogs respond with a threat call (Hunter 2000). In the ACT the method is to systematically survey (call at) all potential breeding pools at a site. This involves up to 10 people (usually 4-6 people) spaced 5–10 m apart walking in a 'sweep line' across a breeding site so that all pools at the site are surveyed (Figure 3). Depending on the width of the walked sweep line and the size of the site, multiple sweeps may need to be done across the site to cover the whole area. When a person on the line encounters a pool, the person stops (and usually so does everyone else in the line) about two metres from the pool and calls once or twice (the call has been standardised to "Hey frog"). If a Corroboree Frog responds, the approximate location of the calling frog in the pool is determined by two people listening at approximately right-angles to the call and estimating the location by triangulation. The location is marked with flagging tape for later follow up to check for a nest site. The number of calling males is used as an index of abundance (population size) at the site.

Figure 5. Map showing the key breeding bogs for Northern Corroboree Frogs in Namadgi National Park. These bogs are regularly monitored for numbers of calling males. Also shown is the ACT/NSW border (shading) and Corin Dam.

Figure 6. Surveys for calling males at Snowy Flats

Since 2017, the annual monitoring has been undertaken by one or two people quietly walking across the sites and surveying pools (rather than a larger sweep line). This change to fewer people is due to a perception by the author gained over the previous few years that at sites where there are very few Corroboree Frogs, the frogs seem to be more hesitant to respond, or to respond more than once, to the shout-response method, especially when there is disturbance (walking, calling) near the pool. Thus pools were approached quietly and the shout-response method was used after a few minutes of listening near the pool. This method appeared to be better at detecting Corroboree Frogs than walking up to every pool and immediately shouting then waiting briefly for a response before moving on. This method (one or two persons quietly walking at a site and surveying pools) was also used during the 2017 survey of historic breeding sites.

Monitoring results

The longest monitoring dataset for Northern Corroboree Frogs in the ACT is from Ginini Flats West in Namadgi National Park (Figure 7). The first survey of calling Northern Corroboree Frog males at this site was undertaken in 1986 (by W. Osborne, then ecologist with the ACT Government) in response to anecdotal evidence that suggested the species might be in decline. The results of intermittent monitoring over the next few years showed a sharp reduction in number of calling males, indicating the population at the site was declining. More intensive (annual) monitoring at Ginini Flats West commenced in 1991, and annual monitoring at other key breeding sites commenced in 1996. The results of all sites (1996 onwards) show a broadly similar trend (Figure 8), suggesting that the pre-1996 decline observed at Ginini West is representative of the magnitude of declines that occurred at other sites in the ACT prior to 1996.

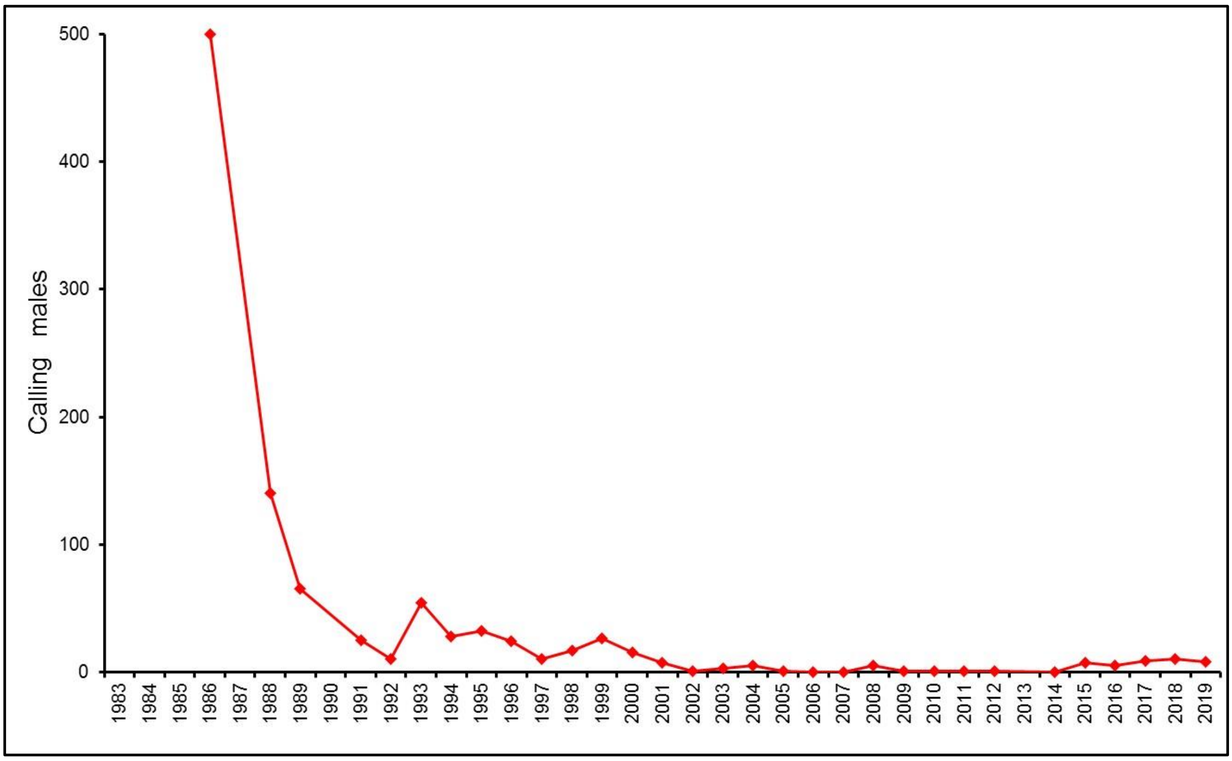

Figure 7. Number of calling males at Ginini Flats West in Namadgi National Park from 1986 to 2018

The monitoring results for Ginini Flats West, Ginini Flats East, Snowy Flats, Cheyenne Flats and Hanging Flat West show a fluctuating though overall downward trend in numbers of calling males, with no calling males detected at any of these sites in 2014 (no monitoring was undertaken in 2013). Corroboree Frogs have not been detected at Cheyenne Flats since 2010 and at Snowy Flats since 2011.

Monitoring results after 2014 show a small increase in calling males at Ginini Flats West and Hanging Flat West, where captive-bred juvenile Corroboree Frogs have been released since 2011 (see section on reintroduction to the wild). There has also been a small increase at a third site (two calling males at Ginini East), though it is uncertain whether these frogs are from individuals released at Ginini Flats West that have travelled 600 m though woodland to Ginini Flats East, or are the progeny of wild individuals that were last known to be present at Ginini Flats East five years previously.

Pools and wet seepage areas in Morass Flats have been intermittently surveyed since 2004. Three small bogs on the slope of Stockyard Spur in Namadgi National Park have been monitored on an intermittent basis, and no Corroboree Frogs have been detected at any of these bogs since 2005.

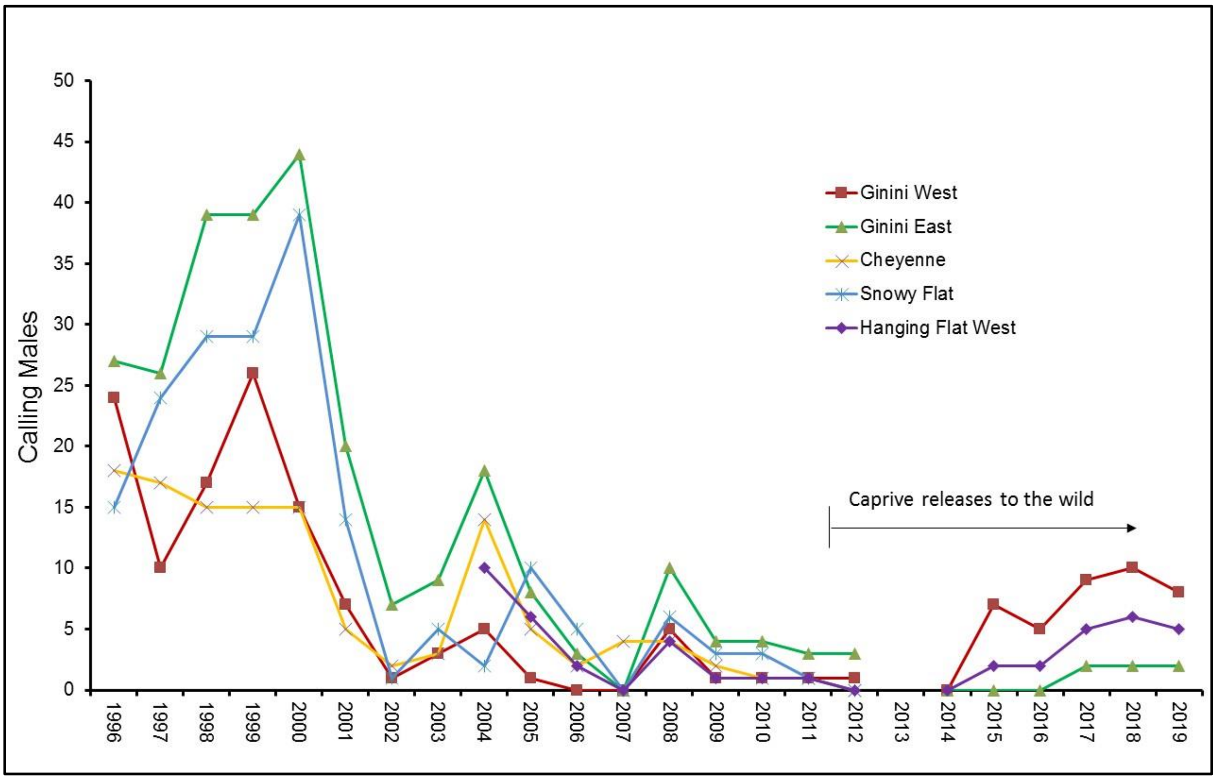

Figure 8. Number of calling males at key ACT breeding sites recorded during annual monitoring surveys that began in 1996.

5 Survey of historic breeding sites

In 2017, a survey was undertaken of 35 locations in the ACT (or in NSW close to the NSW-ACT border) where Northern Corroboree Frogs have been historically recorded with the aim of assessing the current abundance and distribution of Northern Corroboree Frog populations in the ACT, and to undertake a subjective assessment of suitability of habitat for breeding. These historical sites included sites that have been surveyed or intermittently monitored in the past, though many had not been monitored for two decades or more. This 2017 survey was in addition to annual monitoring at the five key historic breeding sites shown in Figure 8.

Survey methods

The survey was undertaken by two observers (Murray Evans and Will Osborne), with each observer surveying sites independently (sites were visited by each observer on different days) and over 90% of sites were visited by both observers. Locations where Northern Corroboree Frogs have been recorded in the ACT were obtained from records held in the ACT Wildlife Atlas database, and from hardcopy topographic maps that were hand-marked with historic locations of Corroboree Frogs by Peter Ormay and Will Osborne, who undertook surveys for the species in the 1990s. A total of 35 sites were identified for survey (Table 1, Figure 9).

Table 1. Sites where surveys were undertaken for Corroboree Frogs during 2017

Site Code	Location Notes	MGA Easting	MGA Northing
F010	Blundell's Flat	666213	6090084
F012	New Chums Road	666395	6082795
F016	Ginini Flats East	660715	6068048
F033	Hanging Bog (near Ginini West)	660913	6067984
F070	Cheyenne Flats	662239	6067587
F099	West of Cheyenne Flats	661227	6066235
F106	Cheyenne Flats	661359	6065966
F110	Stockyard Creek north	661012	6065472
F111	Stockyard Creek	661564	6065429
F112	Stockyard Creek	661807	6065392
F113	Stockyard Creek below arboretum	662013	6065384
F115	Stockyard Creek north x Cheyenne Creek	661776	6065380
F115a	Stockyard Creek north x Cheyenne Creek	661811	6065262
F116	Stockyard Creek	661213	6065084
F117	Stockyard Creek	661213	6064984
F118	Stockyard Creek	660813	6064884
F119	Stockyard Gap	660613	6064784
F120	Stockyard Gap west	660513	6064684
F121	Stockyard Spur	662929	6064606
F122	Stockyard Creek	661005	6064600
F123	Stockyard Creek	661240	6064440
F124	Stockyard Spur	662817	6064331
F125	Stockyard Spur	662941	6064070
F126	Stockyard Spur	6064045	662906
F127	Stockyard Spur	661513	6063984
F154	100m from Mount Franklin Rd	662132	6062310
F167	Mount Franklin Rd	662013	6061484
F168	Mount Franklin Rd	662013	6061084
F169	Mount Franklin Rd	661313	6058684
F170	Mount Franklin Rd	661413	6058584
F171	Mount Franklin Rd	661313	6058384
F172	Cribbs Creek	661413	6057984
F173	Cribbs Creek	661513	6057684
F174	Mosquito Creek	662413	6056384
BOG1	Stockyard Spur	661894	6065311

The survey was undertaken during the last two weeks of February 2017 by quietly walking up to pools or seepage areas at each site and listening for calling frogs for several minutes, after which the shout-response technique was used in an attempt to elicit calls and/or to triangulate locations of calling Corroboree Frogs. The general characteristics of the site were noted, including size and presence of pools, and overall hydration (‘wetness’) which was broadly characterised as low (pools dry/damp), moderate (some pools with water) or high (all pools filled with water), and general vegetation characteristics (particularly presence of sphagnum moss and prevalence of a shrub layer).

Results and discussion of the 2017 survey

Of the 35 historic sites surveyed for calling male Northern Corroboree Frogs in 2017, calling males were found at only two of these sites. These two sites were Stockyard Gap West (F120), where 3 calling males were detected, and at Stockyard Creek site F115a, where 1 male was detected.

Weather conditions during the 2017 survey were drier than average. Figure 10 shows the combined rainfall total for January (the month preceding the surveys) and February (the month the surveys were undertaken). Rainfall during these two months largely determines the hydration levels of breeding sites during the summer survey period. Reflecting the lower than average rainfall during the survey month and the prior month, most sites visited appeared to have low-moderate hydration levels, as evidenced by generally dry ground (soil) conditions with some pools having water but many of the ephemeral pools and seepage areas being moist or dry rather than filled with water. It is possible that the drier than average conditions during the breeding season resulted in fewer Corroboree Frogs calling than during wetter years, though many sites still had pools with water or areas that were damp, and hence the presence of apparently suitable breeding habitat.

A proportion of sites visited did not appear to be suitable breeding habitat (despite historical records of calling males), either because there were no obvious pools or seepage areas, or the shrub layer (Melaleuca and Baeckea) was so dense that no pools or ground layer vegetation (moss or grass) existed under the layer. These sites were typically small bogs surrounded by woodland or forest. The dense shrub layer is likely to have resulted from the 2003 wildfires and general drying out of bogs and seepage areas following the fires, enabling the density of shrubs to increase. It also is possible that the hydrological characteristics of these sites has changed since earlier surveys (some earlier surveys were done more than two decades previously).

The detection of Northern Corroboree Frogs at only two of the 35 historical sites surveyed (and a total of four males in very small bogs) indicates that numbers of the species have declined to extremely low levels in the ACT, and that the species is on the verge of extinction in the wild. Apart from the two reintroduction sites (Ginini Flats West and Hanging Flat West), the only known locations of Corroboree Frogs in the ACT are one of the long-term monitoring sites (Ginini Flats East) (two calling males), and the two small historical sites surveyed in 2017 (total of four calling males).

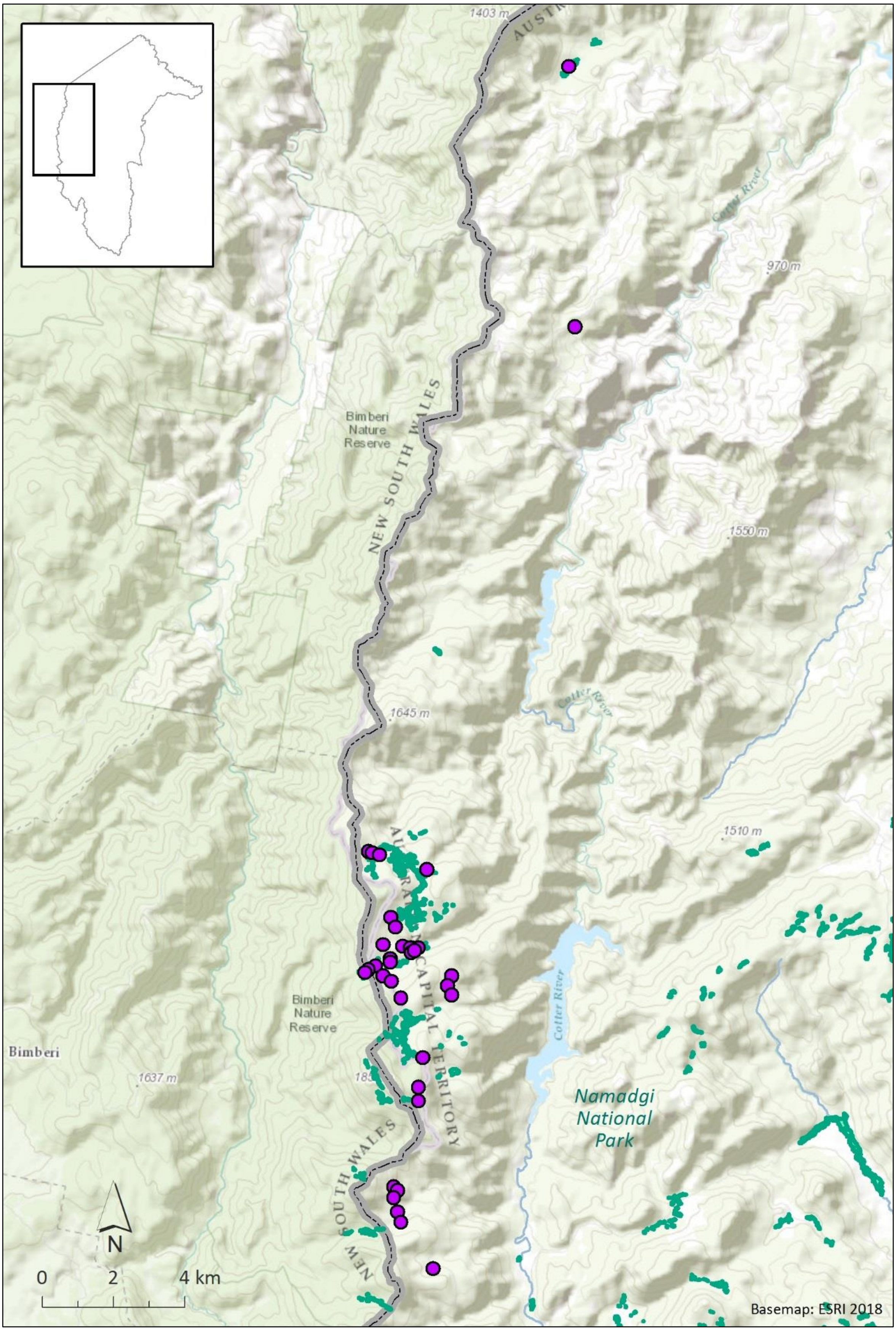

Figure 9. Locations of sites (purple) surveyed in 2017 for Northern Corroboree Frogs. Bogs and fens are shown in green (not all of which are suitable habitat for Corroboree Frogs).

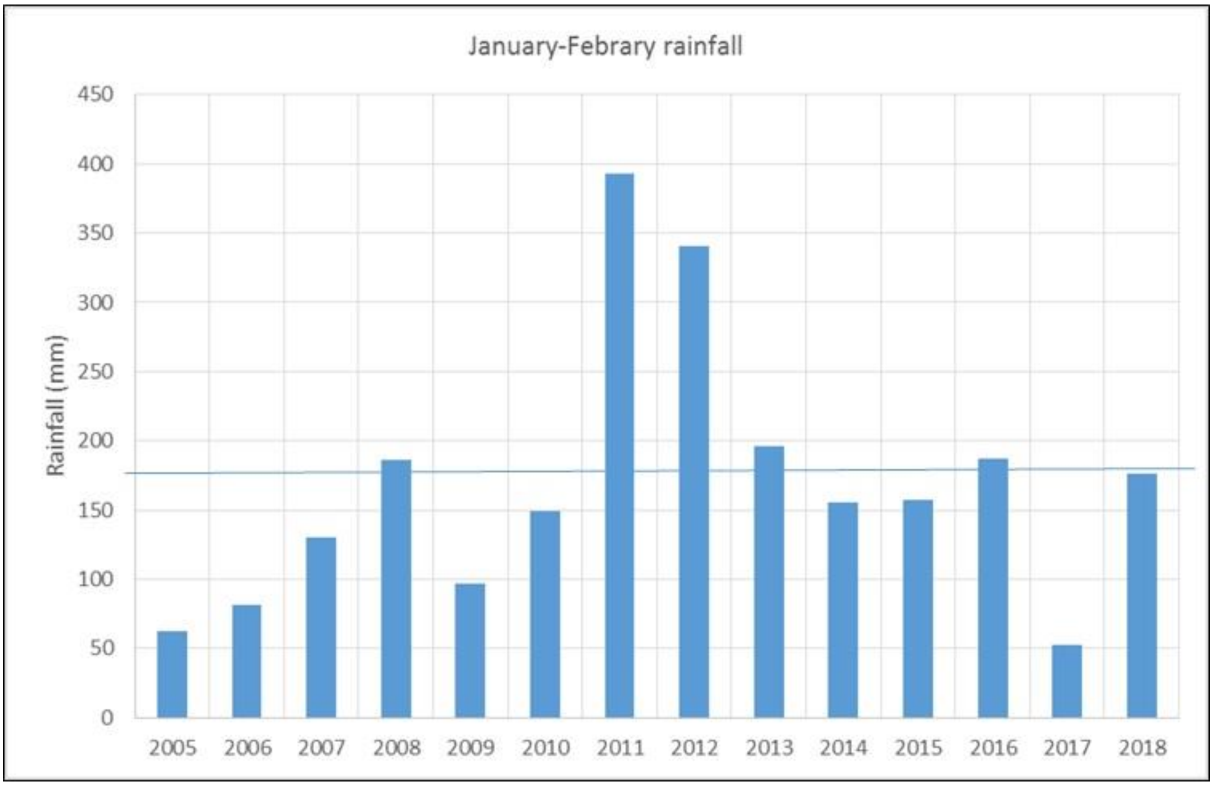

Figure 10. Mt Ginini weather station rainfall totals for mid to late summer (total for January and February) from 2005 to 2018. Horizontal line is the long term (1961-1990) average rainfall for mid to late summer. Mid to late summer is the breeding season for Corroboree Frogs.

6 Captive population of Northern Corroboree Frogs

Aims

The aims of establishing a captive population of Northern Corroboree Frogs are to:

- Maintain an 'insurance' population whilst the species is under immediate threat of extinction in the wild.
- Provide a source of frogs for reintroduction programs.
- Provide a resource for research aimed at assisting recovery of wild populations.
- Serve as an educational resource to increase public awareness of the need for conservation of the species.

Insurance populations

Insurance populations are ex-situ populations that aim to provide some level of insurance against extinction of the species. Such populations are established when threatening process cannot be mitigated to prevent probable extinction of the species, or of genetic units of the species. Insurance populations allow protection of genetically important individuals until the threats to wild populations can be mitigated.

Due to the worldwide decline in amphibians, the establishment of insurance populations has been identified as one of the key actions in the 2007 Amphibian Conservation Action Plan (Mendelson et al. 2007). Because insurance populations typically target the most critically threatened species challenged by threats that tend to be complex and difficult to mitigate, projects involving them are usually long-term and require careful planning of facilities, resources, genetics and management of disease (McFadden et al. 2018). Captive insurance (sometimes called 'assurance') colonies of amphibians have been established for a number of species in Australia and elsewhere as part of the recovery actions for these species (Griffiths and Pavajeau 2008; Germano and Bishop 2009; McFadden et al. 2018).

A key recommendation of the Corroboree Frog National Recovery Team (which consists of members of state conservation agencies, research institutions and zoos) is to:
"Establish and maintain insurance populations of both species of Corroboree Frogs"

Establishing a captive population of Northern Corroboree Frogs at Tidbinbilla Nature Reserve

The population monitoring results leading up to 2002 indicated that numbers of Northern Corroboree Frogs were not recovering from the initial crash that occurred in the 1980s, and despite small but hopeful population increases in 1993, and to a lesser extent in 1999, the decline continued and by 2002 numbers of Corroboree Frogs had dropped to precariously low levels. The reason for the decline was not known, with proposed causes including drought, high UV levels (due to the 'ozone hole') and disease. Although Amphibian Chytrid Fungus had been identified in 1998 (in Queensland) little was known about this fungus and it was not yet attributed to the decline of frogs in the cool Australian Alps region.

In 2002 the decision was made by the ACT Government (Conservation Research section) to establish a captive 'insurance' population from eggs collected from the wild during the next breeding season (2003) as a safeguard against extinction of the species in the ACT. A captive population of Southern Corroboree Frogs had already been established four years previously in Melbourne by the NSW Office of Environment and Heritage, and the Amphibian Research Centre (ARC). A modified refrigerated shipping container was purchased from the ARC by Conservation Research during late 2002. Shipping containers provide a cost-effective method for maintaining captive populations in a controlled, bio-secure environment, and this ARC-pioneered method has been recommended for use in other amphibian conservation programs (Mendelson et al. 2007; Griffiths and Pavajeau 2008).

Before eggs could be collected to establish the captive population of Northern Corroboree Frogs, extensive wildfires severely burnt 90% of Namadgi National Park and much of Kosciusko National Park in January 2003. The fires occurred during the breeding season for Corroboree Frogs and burnt around 80% of summer breeding habitat, and removed almost all of the logs and leaf-litter in the over-wintering woodland habitat. The fires also severely burnt Tidbinbilla Nature Reserve, destroying infrastructure and resulted in loss of almost all of the captive wildlife. Options considered for the location of the new Corroboree Frog shipping container included CSIRO Sustainable Ecosystems (the location of the Conservation Research section) in north Canberra, two local universities and Tidbinbilla Nature Reserve. Despite the loss of infrastructure following the fire, Tidbinbilla NR was selected as the most suitable long-term option. The shipping container arrived at Tidbinbilla NR on 29 May 2003 and was initially located where the animal house / vet facility had existed (lost in the fire) due to the availability of good stream water and the probability that the animal house would be rebuilt at the same site. The new animal house facility was eventually built elsewhere and in 2005 the shipping container was relocated to its present site near the main Tidbinbilla depot. In 2005 a second larger shipping container was acquired by Conservation Research, and was co-located with the first shipping container at the Tidbinbilla depot. In 2007 the facility was expanded with the purchase of a third shipping container, which was outfitted as a dedicated breeding facility.

The captive population of Northern Corroboree Frogs was established with 360 eggs collected by M. Evans (Conservation Research) in March 2003 from the relatively small areas of breeding habitat that had not burnt in the January 2003 wildfires. The collection sites were Ginini Flats West, Ginini Flats East, Snowy Flats, Cheyenne Flats and Hanging Flat West. Amphibian Chytrid Fungus was not yet known to be present in Corroboree Frog populations, nor to be the principal cause of the decline, though fortunately frog eggs are naturally free of Chytrid Fungus (they do not contain keratin which is required by the fungus) and so serendipitously a captive population was established that was free of the fungus. Approximately one third of the eggs were collected from each clutch that was found, which was expected to have a low impact on the population given that most eggs would not survive to be adult frogs. The eggs were placed in damp sphagnum moss and held in a dedicated fridge at 8°C for about 6 weeks until the new shipping container was ready to receive them. Over 80% of these eggs hatched and were raised through to adult frogs. A second egg collection was undertaken in 2004 (220 eggs) and only small egg collections (< 30 eggs annually) were possible between 2005 and 2007 due to the small number of Corroboree Frog egg clutches found. By 2007 so few eggs were able to be found that egg collections from the wild were discontinued.

Based on age to sexual maturity of about 4 years (from eggs) for captive Southern Corroboree Frogs, it was likely that the oldest captive Northern Corroboree Frogs at Tidbinbilla had reached sexual maturity in 2007 and so an attempt was made to breed them in 2008 in a shipping container set up with terrariums containing artificial sphagnum moss bogs. Up to that point, attempts to breed the Southern Corroboree Frog had been largely unsuccessful and it was not known whether Corroboree Frogs could be maintained in captivity as self-sustaining populations. At Tidbinbilla NR, approximately 20% of Northern Corroboree Frog females laid eggs (total of 180 eggs) during the first breeding attempt (2008 breeding season), which is the first time the species had been bred in captivity. Due to lack of space, the third shipping container that had been acquired in late 2007 was set up as a dedicated breeding unit for the 2009 breeding season. In the second breeding attempt (2009 breeding season) around 1000 eggs were produced from the breeding population, which numbered around 400 frogs (males and females) in the two shipping containers dedicated to breeding. Since 2007 the captive population at Tidbinbilla NR has numbered between 500 and 1500 frogs, and since 2009 between 300 and 1000 eggs have been produced annually from the captive population. In 2019 around two-thirds of the original wild founders (collected as eggs in 2003 and 2004) of the captive population were still alive and breeding (all aged between 14 and 15 years old since laid as eggs).

The captive population of Northern Corroboree Frogs at Tidbinbilla occupies three shipping containers that serve as a bio-secure facility, with all water entering the facility being filtered of physical, chemical and biological contaminants. Two shipping containers are dedicated to breeding and one shipping container is dedicated to raising frogs from eggs to adults. The shipping containers also allow the environmental conditions (temperature, moisture, photoperiod) experienced by the frogs to be controlled, allowing recreation of the natural environmental conditions experienced in the wild or creation of artificial environmental regimes. Since 2003, Conservation Research has supported a dedicated Wildlife Officer to undertake the day-to-day husbandry of the captive Corroboree Frog population at Tidbinbilla Nature Reserve.

By 2005 the primary cause of frog declines (including Corroboree Frogs) was suspected to be Amphibian Chytrid Fungus (Skerratt et al. 2007), which was subsequently confirmed to be widespread in wild Corroboree Frog populations (Hunter et al. 2010). Infection by Amphibian Chytrid Fungus continues to be the main threat to Corroboree Frogs in the wild and to the captive population at Tidbinbilla NR. The Corroboree Frog breeding facility (the three shipping containers) is not open to public (for bio-security reasons) and a strict hygiene and quarantine protocol is followed by the few staff that have access to the facility for day-to-day husbandry purposes.

Given the high value of an insurance population, the risk of losing the captive population of Corroboree Frogs through catastrophe (disease outbreak, equipment failure, fire etc.) must be minimised. A key step that has been taken to reduce risk to the captive population at Tidbinbilla is to distribute individuals between more than one shipping container. Currently the population occupies three shipping containers. Each shipping container is a separate bio-secure facility, which reduces the risk of a disease outbreak in one container spreading to the rest of the captive population. The three shipping containers also receive water via two separate water filtration and storage systems and the shipping containers have independent refrigeration units, electrical systems and climate control units, all of which is designed to provide redundancy of critical equipment and hence backup in the event of equipment failure. The facility is also designed to be quickly and easily connected to a trailer-mounted generator in the event of a prolonged electrical blackout.

Another key step in minimising risk to the captive population is to disperse the population amongst multiple locations, which provides added security in the event of disease outbreak or widespread fire. Zoos or other institutions that have the necessary facilities and expertise to maintain Corroboree Frogs would provide suitable additional locations. Activities that maintain wild populations (such as release of post-metamorphic frogs) can also contribute to minimising risks to the assurance population because the total number of corroboree frogs is divided between captive and wild populations. However, the benefit of reduced risk to captive populations of dividing individuals between captive and free-living populations needs to consider the risks to wild individuals from potentially higher mortality rates and effects of stochastic environmental events (wildfire, drought etc). A second smaller captive population has been established at Healesville Sanctuary in Victoria, with individuals sourced from the Tidbinbilla captive population (F1 generation, original founders from Ginini Flats).

7 Reintroduction to the wild

Aims

The aims of releasing captive-reared Northern Corroboree Frogs to Namadgi National Park are to:

- Increase the size of existing populations to help buffer them against environmental and demographic stochasiticity and loss of genetic diversity, to which small populations are highly susceptible, and to enable functioning social systems (i.e. natural breeding behaviour including chorus and mate choice).
- Provide the opportunity for wild populations to acquire natural resistance to Amphibian Chytrid Fungus through natural selection by facilitating populations to persist in the wild in the presence of the fungus.
- Re-establish populations that have become locally extinct.

Amphibian reintroduction overview

Reintroduction to the wild of captive-reared individuals has been undertaken for a range of animal taxa including amphibians (see reviews by Dodd and Seigel 1991; Fischer and Lindenmayer 2000; Griffiths and Pavajeau 2008) and is increasingly being used as a conservation tool for threatened species recovery.

Translocations/reintroductions of wild animals have generally been more successful than using captive animals (Griffith et al. 1989; Fischer and Lindenmayer 2000), though this does not appear to be the case with amphibians where success rates are similar for captive or wild releases (Germano and Bishop 2009). A number of traits make amphibians good candidates for captive-release programs, including high fecundity, lack of parental care and behaviours that are genetically hard-wired rather than learnt (Germano and Bishop 2009). However, there is still much to be learnt about reintroductions, as only about half of the published amphibian translocation/reintroductions were reported as successful, the other half were either failures or uncertain. Of the reported causes of failure, the most common for amphibians were movement away from the release site (homing and large-scale movements) and poor quality habitat.

Typically, reintroduction of wildlife should only be undertaken once the threats that caused the species' decline have been removed or ameliorated (IUCN/SSC 2013). Amphibian Chytrid Fungus is a threat to amphibians that is complex and unlikely to be eradicated from the environment. This fungus has caused the decline, and in some cases extinction, of many frog species in Australia and elsewhere, though some frog species in Australia that have undergone population declines are now persisting at low population levels naturally or are recovering (Scheele et al. 2014, 2017). Amphibian Chytrid Fungus is still present in these populations, suggesting these species are surviving with the fungus though behaviours that ameliorate the effect of the disease (such as selecting environmental refugia in sites that avoid disease outbreaks), or through altered life-history strategies (producing offspring at a younger age before adults become infected) or have developed natural resistance to the disease. For natural disease resistance to develop, populations must persist in the wild for sufficient time for resistance to develop.

Releases of Northern Corroboree Frogs to Namadgi National Park

A key aim of the reintroduction of Northern Corroboree Frogs to Namadgi National Park is to maintain wild populations in the presence of Chytrid Fungs to allow natural resistance to develop. These reintroductions are experimental because it is not known whether Northern Corroboree Frogs have the capacity to develop natural resistance to Chytridiomycosis, or how long this may take. The reintroductions will also help to identify the number of individuals required to be released annually to maintain wild populations and whether this strategy is successful, or even feasible over the longer term.

The pre-metamorphic life stages (eggs and tadpoles) of Corroboree Frogs are highly susceptible to desiccation from varying rainfall patterns and, apart from Amphibian Chytrid Fungus, this is apparently the greatest source of mortality in wild populations (Hunter 2000, Hunter pers. comm.). Breeding and 'head-starting' in captivity are important techniques to substantially increase recruitment to wild (or captive) populations by avoiding this pre-metamorphic mortality barrier. Northern Corroboree Frogs can be 'head-started' by collecting eggs from the field, raising them in captivity though to the post-metamorphosis stage (frogs) and then releasing the frogs back to the wild. Alternatively, frogs bred in captivity and raised to the post-metamorphosis stage may be released to the wild.

The captive breeding and reintroduction program for Northern Corroboree Frogs can be conceptualised as shown in Figure 11. Following the decline of wild populations a captive insurance population is founded. Once this captive population is established and can be maintained through captive breeding, progeny from the captive population can be reintroduced back to the wild to increase the size of wild populations. The captive breeding program for Northern Corroboree Frogs has passed through the founding and growth stages and the captive population can be maintained through breeding. The captive population is producing progeny excess to maintenance requirements and so has entered the reintroduction stage.

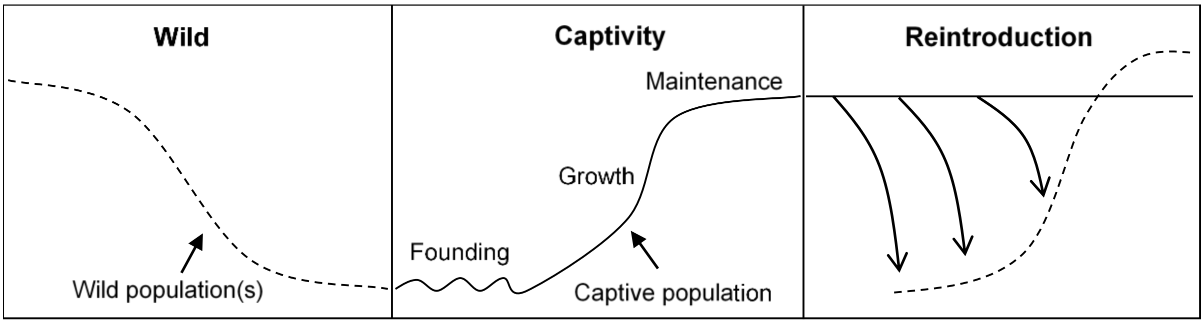

Figure 11. Conceptual process for using captive breeding to re-establish wild populations (adapted from Frankham et al. 2004).

The experimental release of captive-bred Northern Corroboree Frogs aims to augment Northern Corroboree Frog populations at two sites in Namadgi National Park; Ginini Flats West and Hanging Flat West. Ginini West was chosen because it is a relatively large site, it was historically a significant breeding site, wild Corroboree Frogs were present at the site until relatively recently (2012), and it has lower public visitation levels compared to other large sphagnum moss bogs sites. Hanging Flat

West was chosen because it is a small site (to contrast to the larger Ginini Flats West site), wild Corroboree Frogs were present at the site until relatively recently (2011), and it is remote from, and not connected to, other wetlands/bogs and hence it is thought that released frogs may be less likely to disperse away from the site.

Northern Corroboree Frogs have been released to these sites annually since 2011. The released frogs were bred at Tidbinbilla NR as part of the captive-breeding program (see section on establishing a captive population). A small proportion of frogs released were bred at Healesville Sanctuary, which are progeny from frogs transferred from Tidbinbilla NR to Healesville Sanctuary in 2010). These Healesville frogs are F1 generation bred from wild eggs collected from Ginini Flats West and Ginini Flats East. Almost all frogs released were juvenile frogs (about 1 year old since metamorphosis), which means they will not be able to be detected (heard) at release sites until they reach breeding age at three or four years since metamorphosis (two to three years following release).

Captive-bred frogs were released as juveniles rather than adults to minimise the time they spent in captivity so that they did not become habituated to 'soft' captive conditions, and allow them to become fully adapted to wild conditions by the time they reached breeding age. Mortality rates in captive (and presumably wild) Corroboree Frogs are higher when they have recently metamorphosed and lower when they reach about one year post-metamorphosis, and so this age were chosen as the earliest that frogs were sufficiently robust for release. The NSW Office of Environment and Heritage and Taronga Zoo have been experimenting with releasing captive-bred Southern Corroboree Frogs as eggs and as adult frogs, and so juveniles were chosen for Northern Corroboree Frogs for release to Namadgi NP to form part of a larger experiment to look at any differences in these age-based release strategies. In addition to annual releases of juvenile frogs, there have been two releases as eggs to Ginini Flats East, which were undertaken during years when the high numbers of eggs were produced in captivity exceeded the space available for raising all of the eggs to frogs. Ginini East was chosen as a third release site with the aim of assessing the success of egg releases by monitoring this site for calling males 4 to 5 years subsequently, which is when any surviving eggs/frogs are expected to reach breeding age. The numbers of frogs released to sites in Namadgi National Park are given in Table 2.

Table 2. Number of Northern Corroboree Frogs released to Namadgi National Park

Year	Site	Date released	Life stage	Number	Year laid as eggs
2011	Ginini Flats West	24/11/2011	Frog	50	2009
2011	Ginini Flats West	24/11/2011	Frog	67	2010
2011	Hanging Flat West	23/11/2011	Frog	33	2009
2011	Hanging Flat West	23/11/2011	Frog	50	2010
2012	Ginini Flats West	21/09/2012	Frog	142	2011
2012	Hanging Flat West	21/09/2012	Frog	47	2011
2013	Ginini Flats West	11/12/2013	Frog	160	2012
2013	Hanging Flat West	11/12/2013	Frog	48	2012
2014	Ginini Flats East	22/05/2014	Egg	1278	2014
2014	Ginini Flats East	22/05/2014	Tadpole	9	2014
2014	Ginini Flats West	24/09/2014	Frog	519	2013
2014	Hanging Flat West	24/09/2014	Frog	66	2012
2015	Ginini Flats West	15/10/2015	Frog	512	2014

2015	Hanging Flat West	15/10/2015	Frog	46	2014
2016	Ginini Flats East	02/06/2016	Egg	230	2016
2016	Ginini Flats East	18/08/2016	Egg	241	2016
2016	Ginini Flats West	01/12/2016	Frog	443	2015
2016	Hanging Flat West	01/12/2016	Frog	50	2015
2017	Ginini Flats East	19/10/2017	Egg	33	2017
2017	Hanging Flat West	21/11/2017	Frog	28	2016
2017	Ginini Flats West	21/11/2017	Frog	165	2016
2018	No releases				
2019	No releases				

All frogs released between 2011 and 2016 had their belly patterns photographed to enable subsequent identification in the field. Pattern matching software (Stripe-spotter, Lahiri 2011) was used to search for matching belly patterns in photographs. Belly pattern photographs were discontinued in 2017 because the software failed on occasion to find matches that existed, leading to erroneous conclusions. The sheer number of photographs in the database meant that it was not practical to do manual searching and matching.

Results and discussion of releases to Namadgi National Park

The first Northern Corroboree Frogs were released to Namadgi National Park in 2011. This release involved a total of 200 frogs, all approximately one year post metamorphosis. The results of this release are shown in Figure 8, with the first calling males being detected in 2015, four years following release. In the intervening period (2011 to 2015) wild calling males declined to zero during annual monitoring, indicating that wild populations had become locally extinct or were extremely small. It is highly likely that all (or almost all) of the frogs calling at the release sites in 2015 and subsequently are frogs that have been released from captivity. In 2015 two calling males were able to be located from their calls and their belly patterns photographed, and both were from releases in 2011. The appearance of calling males four years post-release was a year later than expected, indicating the young frogs released in 2011 matured at a slower rate in the wild compared to captivity (most likely due to differences in food availability and temperature).

The total number of calling males at the two release sites in 2015 was nine (seven from Ginini West and two from Hanging Flat). Assuming an equal sex ratio for the group of frogs released in 2011, around 10% of these frog were present in 2015. The number of calling males at the release sites has increased since 2015, which is the result of annual releases of frogs since 2011. Fewer males were heard in 2019 compared to 2018, which might reflect the number of males in the wild, but could also be due to the windy conditions during monitoring affecting the frogs and resulting a lower proportion of males responding to the shout-response technique.

Of the frogs that are ‘missing’ since their release (that is, they are not present at release sites by the time they reach breeding age), it is not known what proportion died (from natural causes and from Chytrid Fungus) and what proportion dispersed away from the release sites during the four year interval between 2011 and 2015. Corroboree Frogs are known to move a few hundred metres from breeding sites into surrounding woodlands (Osborne 1988 and unpublished) and so it is possible that some of the released frogs dispersed away from the release site during the four years prior to reaching breeding age. Two calling males appeared at Ginini East during 2017, after no calling males had been recorded at that site since 2014. Ginini East is approximately 600 m from Ginini West and so it is possible these males had moved from Ginini West.

In 2018 there were a total of 18 calling males at the release sites. Assuming that there is an equal number of breeding age females present, that suggests a breeding population of around 36 frogs at the release sites. In 2017 a clutch of eggs was found at Ginini West and they were taken back to the captive colony to incorporate their genes back into the captive population. The belly pattern of the male found on the nest indicated he had been released in 2013. A clutch of eggs was also found in 2017 at Ginini East and taken back to the captive population, though the male was not in the nest so the origin (captive-bred or wild) of the breeding frogs cannot be confirmed.

Population modelling of releases of Northern Corroboree Frogs

Based on numbers of frogs released annually and the number of calling males detected in each year, basic population (demographic) modelling suggests that released frogs have an annual retention rate of between 50% and 60%. That is, around half of the frogs released in any year will still be retained at the site in the following year, and around half of those frogs will be retained the next year, and so on. The term retention rate is being used here instead of survival rate because an unknown proportion of frogs that are released may survive but disperse away from the release sites. This annual retention rate of between 50% and 60% is based only on four years of calling males, and so additional data on numbers of calling males over the next few years will enable the retention rate to be more accurately determined. However, the rate calculated for Northern Corroboree Frogs released in this program is similar to that calculated for annual survivorship of wild Southern Corroboree Frogs (Hunter 2000).

Figure 12 shows the modelled output of the number of frogs in the wild (total for both release sites) when 200 juvenile (1 year since metamorphosis) frogs are released each year and the annual retention rate is 55% across all years and age classes. Other model parameters are that the sex ratio is even, the frogs live for nine years, and there is no recruitment to the population from breeding in the wild. In reality the retention rate is unlikely to be the same for all years (different climatic conditions) or for all ages, and so the model provides a guide (or an average of all years and ages) rather than showing accurate numbers present at sites.

In Figure 12, the total number of frogs at release sites begins to increase from year 2011 (when the first releases occurred) because of constant releases (additions) of 200 frogs to the wild population each year. The total number stabilises at about 450 frogs (the total for both sites). The population does not continue to increase even though 200 frogs are added each year because annual wild recruitment is not built into the model, and the constant annual additions balance the constant retention (or loss) rate. Wild recruitment is not part of the model because all eggs found in the wild will be brought back to the captive breeding facility at Tidbinbilla NR. The model shows the number of breeding age frogs is about 40, which is about 10% of the total number of frogs estimated to be present at the release sites. Most of the frogs in the wild in the model are pre-breeding age classes.

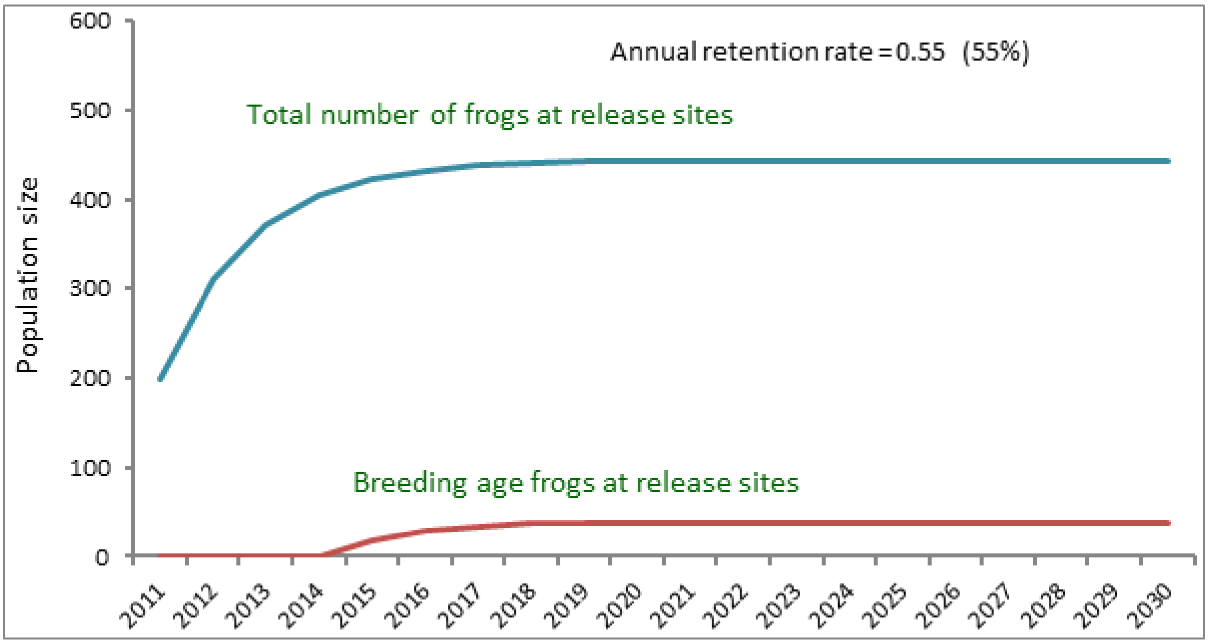

Figure 12. Modelled numbers of frogs at release sites, when 200 juvenile (1 year since metamorphosis) frogs are released annually. The model shows total numbers of frogs in the wild (blue line), and the number of frogs that have reached breeding age (red line). The model does not include wild recruitment.

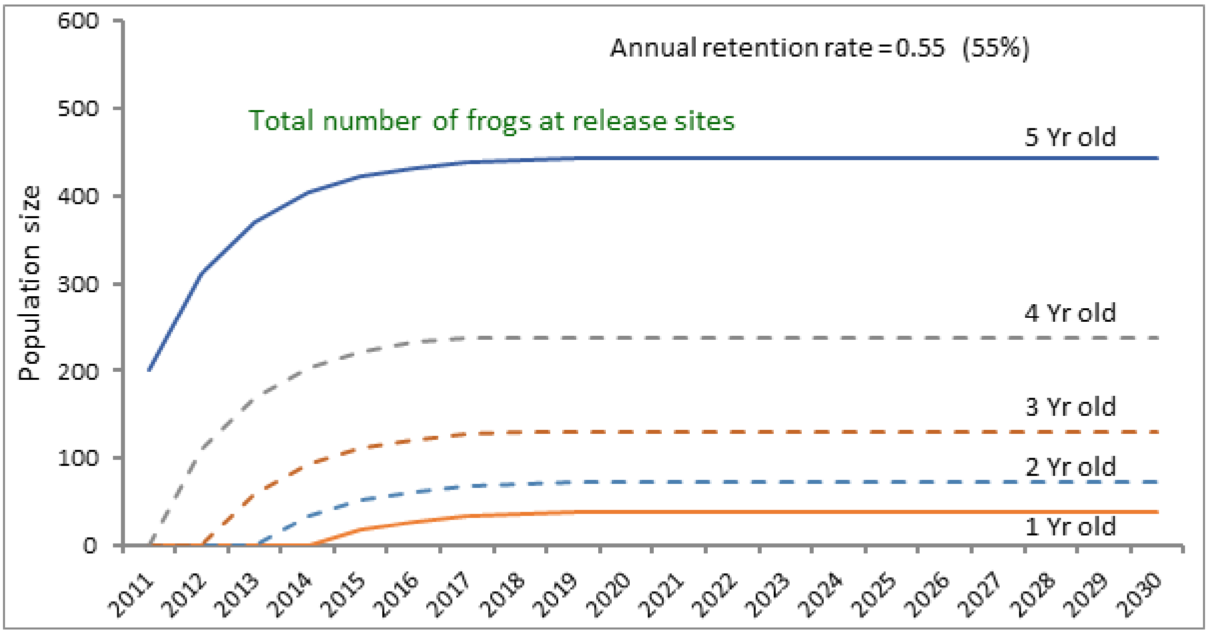

Figure 13. Modelled total number and breeding age frogs at release sites, when 200 juvenile frogs are released annually. Each line shows the effect of annual releases 200 frogs of a particular age. The model does not include wild recruitment.

Given the relatively high rate of annual loss (mortality and probably dispersal) of frogs from the release sites, a logical way to increase the size of the breeding population at release sites is to release frogs at older ages (closer to breeding age). Figure 13 shows the effect of releasing frogs at 1, 2, 3, 4 and 5 years post-metamorphosis. Model parameters are the same as for the previous model (Figure 12), with different lines representing the number of breeding age frogs present if all frogs were to be released at a given age. For example, if all of the 200 frogs released each year were four years old, then the number of breeding age frogs (about 240) is about half the total number of frogs at sites.

Irrespective of the age frogs are released, the total number of frogs at release sites remains about 450. If all frogs are released at 5 years old (breeding age) then all frogs at release sites are of breeding age (i.e. total number of wild frogs = number of breeding age frogs). Note that the model provides an approximation rather than showing what actual numbers will be for each age class of frogs released.

Table 3 shows the modelled size of the wild breeding population for annual releases of frogs that are 1, 2, 3, 4 or 5 years post-metamorphosis, and for annual numbers released varying between 50 and 200 individuals. All other model parameters are the same as the previous Figures. For example, if 200 frogs are released annually, and all frogs are 3 years old (since metamorphosis), then the model indicates the wild breeding population will stabilise at about 128 frogs. The table shows that annual releases of 50 frogs that are 4 years old would result in about the same number (or slightly more) wild breeding age frogs as the current strategy of releasing 200 frogs that are 1 year old.

Table 3. Modelled output of the number of wild breeding frogs for varying age since metamorphosis of frogs released and number released.

Annual number released	Age at release	Resultant size of wild breeding population
50	1	10
100	1	19
150	1	29
200	1	39
50	2	18
100	2	35
150	2	53
200	2	70
50	3	32
100	3	64
150	3	96
200	3	128
50	4	58
100	4	116
150	4	174
200	4	232
50	5	106
100	5	211
150	5	317
200	5	422

8 Future directions

The recovery program for the Northern Corroboree Frog in the ACT began with the establishment of the captive insurance population at Tidbinbilla Nature Reserve in 2003, although the principal causal agent of decline (Chytrid Fungus) was not identified until several years later. Research into overcoming Chytrid Fungus is still an active area around the globe, and includes recent research by Kosch et al. (2018) on genetic resistance of Corroboree Frogs to Chytrid Fungus. While there remains a significant chance that Corroboree Frogs can be re-established in the wild, the National Recovery Team for Corroboree Frogs recommends that captive insurance populations (such as that at Tidbinbilla NR) be maintained. As noted by McFadden et al. (2018) amphibian recovery programs involving insurance populations and overcoming complex threats in the wild such as Chytrid Fungus are likely to require long-term commitments.

There are few avenues of recovery available for amphibians faced with the threat of Chytrid Fungus. In addition to laboratory work involving research into the disease and genetic resistance in frogs, the reintroduction of Corroboree Frogs back to the wild to facilitate development of natural resistance has been identified by the National Recovery Team as an avenue that should be pursued. The captive insurance population at Tidbinbilla NR produces progeny in excess to that required to maintain the captive population, and this progeny is available for reintroduction programs. Experimental releases back to the wild using excess progeny from the captive insurance population incurs relatively little extra cost to the recovery program.

Experimental reintroduction of Northern Corroboree Frogs back to Namadgi NP to establish and maintain wild breeding populations has been a key aim of the ACT Action Plan (ACT Government 2011) and the National Recovery Plan (OEH 2012) for the species, and this should continue under the guidance of the National Recovery Team for Corroboree Frogs, until such time as the National Recovery Team recommends otherwise (for example, the excess progeny can be more gainfully used in other programs or the experimental reintroductions are considered to be unsuccessful). The National Recovery Team includes the ACT Government (represented by ecologists from Conservation Research and wildlife staff from Tidbinbilla Nature Reserve).

Maintaining larger, rather than smaller, breeding aggregations in the wild is likely to result is more successful breeding (larger groups of calling males may help attract/direct females from surrounding woodlands, and possibly other males, to breeding sites), and wider range of pools will be used for nest sites which may help to overcome random effects such as some pools or nest sites not being viable. Overcoming random genetic drift so that genes resistant to Chytridiomycosis become prevalent in the population is also a consideration (small populations are more susceptible to drift) and so the wild and captive populations should be considered together (as a larger metapopulation).

Aiming to maintain a <u>minimum</u> of 60 breeding age frogs in the wild (though preferably 100), spread across two sites, is a reasonable and achievable goal for the ACT recovery program. Modelling of Northern Corroboree Frog reintroductions back to Namadgi NP (Section 7) suggests significant gains can be made towards increasing the number of breeding frogs in the wild by releasing older frogs. The use of the outdoor ring tanks (currently being established at Tidbinbilla NR) should be pursued as a means of expanding the capacity of the Tidbinbilla Corroboree Frog facility to raise frogs to older ages for release. Frogs released to the wild as young juveniles appear to take an extra year to reach breeding age compared to frogs raised in captivity at Tidbinbilla. This suggests that frogs held back in captivity will have the advantage of accelerated maturity and hence if released at three years of age are probably closer in development to 4-year old wild frogs that were released as 1-year old frogs. The modelling suggest that to maintain about 30 breeding age frogs at two sites (total 60 breeding age frogs) would require about 50 frogs to be released annually that are 4 years old (since metamorphosis) (Table 3). It is likely that these captive-raised 4 year old frogs are at breeding age which may mean that the wild breeding population is augmented more than suggested by the numbers in Table 3 (i.e. similar to releasing 50 frogs that are 5 years of age).

Snowy Flats should be considered as another large release site, in addition to the long-term large release site of Ginini Flats West. Corroboree Frogs have not been released at Snow Flats because it has served as a control site to contrast to the experimental reintroduction sites. The evidence is strong that the increase in numbers at Ginini West and Hanging Flat West is due to reintroduced frogs and not from a population increase in wild frogs (which would also be seen across other sites including Snowy Flats) and so Snowy Flats is no longer required as a control site. Snowy Flats has the advantage that it was a key historic breeding site, it still has suitable breeding habitat, and it is an easily accessible site. The small Hanging Flat West site is small and difficult to access, and it is recommended that in future Snowy Flats take priority for releases over Hanging Flat West, which may mean the Hanging Flat West site is discontinued as a release site.

In addition to releases at the two suggested release sites (Ginini West and Snowy Flats), there is scope for novel approaches to re-establishing wild populations, such as experimental releases into areas that may not favour other frog species (such as the Common Eastern Froglet, that carries Chytrid Fungus) or habitats that do not favour Chytrid Fungus). This research is the subject of a new project between the ACT Government and the Australian National University.

9 References

ACT Government 2011. Northern Corroboree Frog (*Pseudophryne pengilleyi*). *Action Plan No. 6. Second edition*. ACT Government, Canberra.

Berger L, Speare R, Daszak P, Green DE, Cunningham AA, Goggin CL, Slocombe R, Ragan MA, Hyatt AD, McDonald KR, Hines HB, Lips KR, Marantelli G and Parkes H. 1998. Chytridiomycosis causes amphibian mortality associated with population declines in the rain forests of Australia and Central America. Proceedings of the National Academy of Science, USA 95: 9031-9036.

Berger L, Longcore J, Speare R, Hyatt A, Skerratt LF. 2009. Fungal Diseases in Amphibians. Pp 2986-3052 in: *Amphibian Biology, Volume 8 Amphibian Decline: Disease, Parasites, Maladies, and Pollution.* Edited by H Heatwole and JW Wilkinson, Surrey Beatty and Sons. NSW.

Brannelly A, Webb RJ, Hunter DA, Clemann N. K. Howard NK, Skerratt LF, Berger L. and Scheele BC 2017. Non-declining amphibians can be important reservoir hosts for amphibian chytrid fungus. *Animal Conservation* https://doi.org/10.1111/acv.12380.

Caldwell JP, Thorp JH and Jervey TO. 1983. Predator prey relationships among larval dragonflies, salamanders and anurans. *Oecologia* 46: 285-289.

Caughley G and Gunn A. 1996. *Conservation Biology in Theory and Practice*. Blackwell Science, London.

Dodd CK and Seigel RA. 1991. Relocation, repatriation, and translocation of amphibians and reptiles: are they conservation strategies that work? *Herpetologica* 47: 336-350.

Duellman WE and Trueb L. 1986. *Biology of Amphibians*. McGraw-Hill, New York.

Fischer J and Lindenmayer DB. 2000. An assessment of the published results of animal relocations. *Biological Conservation* 96: 1–11.

Germano JM and Bishop PJ. 2009. Suitability of Amphibians and Reptiles for Translocation. Conservation Biology 23: 7-15.

Gillespie GR, Hunter D, Berger L, and Marantelli G. 2015. Rapid decline and extinction of a montane frog population in southern Australia follows detection of the amphibian pathogen *Batrachochytrium dendrobatidis*. *Animal Conservation*, 18. pp. 295-302.

Green K and Osborne WS. 1994. *Wildlife of the Australian Snow-Country*. Reed, Sydney.

Griffiths RA, and Pavajeau L. 2008. Captive Breeding, Reintroduction, and the Conservation of Amphibians. *Conservation Biology*, 22: 852–861

Heyer WR, Donnelly MA, McDairmid RW, Hayek LC and Foster MS (eds). 1975. Measuring and Monitoring Biological Diversity. *Standard Methods for Amphibians*. Smithsonian Institute Press, Washington.

Hunter D. 2000. Population demography and conservation of the Southern Corroboree Frog. Master of Applied Science Thesis. University of Canberra.

Hunter D. 2001. Surveys and monitoring of threatened frog species in South-eastern New South Wales between October, 2000 and March, 2001. Unpublished report to the NSW National Parks and Wildlife Service.

Hunter D, Osborne W, Marantelli G and Green K. 1999. Implementation of a population augmentation project for remnant populations of the Southern Corroboree Frog (*Pseudophryne corroboree*). Pp 158-167 in *Declines and Disappearances of Australian Frogs* ed by A. Campbell. Environment Australia: Canberra.

Hunter D and Osborne W. 2000. Recovery plan actions completed by the University of Canberra for the Southern Corroboree Frog, *Pseudophryne corroboree*: Annual Report. Unpublished report to the National Parks and Wildlife Service.

Hunter D, Osborne W, Smith M and McDougall K. 2009a. Breeding habitat use and the future management of the critically endangered Southern Corroboree Frog. *Ecological Restoration and Management*, 10: 103-109.

Hunter D, Pietsch R, Clemann N, Scroggie M, Hollis G. and Marantelli G. 2009b. Prevalence of the amphibian chytrid fungus (*Batrachochytrium dendrobatidis*) in populations of two frog species in the Australian Alps. Heidelberg: Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment.

Hunter DA, Speare R, Marantelli G, Mendez D, Pietsch R and Osborne W. 2010. Presence of the amphibian chytrid fungus, *Batrachochytrium dendrobatidis*, in threatened corroboree frog populations in the Australia Alps. *Diseases of Aquatic Organisms*, 92: 209-216.

Hunter D, Clemann N, Coote D, Gillespie G, Hollis, G Scheele B, Philips A. and West M. 2018. Frog declines and associated management response in south-eastern mainland Australia and Tasmania. Pp 39-58. In *Status of conservation and decline of Amphibians: Australia, New Zealand and Pacific islands*. Eds H. Heatwole and J Rowley. CSIRO Publishing Australia.

IUCN/SSC. 2013. Guidelines for Reintroductions and Other Conservation Translocations. IUCN Species Survival Commission Gland, Switzerland.

Kosch TA, Silva CNS, Brannelly LA, Roberts AA, Lau Q, Berger L and Skerratt LF. 2018. Genetic potential for disease resistance in a critically endangered frog decimated by chytridiomycosis. bioRxiv preprint online doi: http://dx.doi.org/10.1101/247999. Accessed November 2018.

Kriger KM, and Hero J-M. 2006. Survivorship in wild frogs infected with chytridiomycosis. *Ecohealth* Vol 3, pp 171–177.

Lahiri M, Tantipathananandh C, Warungu R, Rubenstein DI, Berger-Wolf TY. 2011. Biometric Animal Databases from Field Photographs: Identification of Individual Zebra in the Wild. Proceedings of the ACM International Conference on Multimedia Retrieval (ICMR 2011), Trento, Italy, 2011

Lindenmayer D and Burgman M. 2005. *Practical Conservation Biology*. CSIRO Publishing, Australia.

McDonald K, Alford R. 1999. A review of declining frogs in northern Queensland. Pp 14-22. In *Declines and Disappearances of Australian Frogs*. Ed by A. Campbell. Environment Australia, Canberra.

McFadden MS, Gilbert D, Bradfield K, Evans M, Marantelli G and Byrne P. 2018. The role of ex-situ amphibian conservation in Australia. Pp 125-140. In *Status and conservation decline of amphibians. Australia New Zealand and Pacific Islands.* Eds H Heatwole and J Rowley. CSIRO Publishing, Australia.

Mendelson JR III, Gagliardo R, Andreone F, Buley KR, Coloma L, Garcia G, Gibson R, Lacy R, Lau MW, Murphy J, Pethiyagoda R, Pelican K, Pukazhenthi BS, Rabb G, Raffaelli J, Weissgold B, Wildt D and Xie Feng. 2007. Captive programs. Pages 36–37 in C Gascon, JP Collins, RD Moore, DR Church, JE McKay and JR Mendelson III, editors. *Amphibian conservation action plan*. IUCN/SSC Amphibian Specialist Group, Gland, Switzerland,and Cambridge, United Kingdom.

Morgan MJ, Hunter D, Pietsch R, Osborne W and Keogh JS. 2008. Assessment of genetic diversity in the critically endangered Australian corroboree frogs, *Pseudophryne corroboree* and *Pseudophryne pengilleyi*, identifies four evolutionarily significant units for conservation. *Molecular Ecology* 2008: 17, 3448–3463.

Murray KA, Skerratt LF, Speare R, McCallum H. 2009. Impact and dynamics of disease in species threatened by the amphibian chytrid fungus, *Batrachochytrium dendrobatidis*. *Conservation Biology* 23: 1242-1252.

Murray K, Retallick R, McDonald KR, Mendez D, Aplin K, Kirkpatrick P, Berger L, Hunter D, Hines HB, Campbell R, Pauza M, Driessen M, Speare R, Richards SJ, Mahony M, Freeman A, Phillott AD, Hero J-M, Driscoll D, Puschendorf R, Skerratt, L.F. 2010. The distribution and host range of the pandemic disease chytridiomycosis in Australia spanning surveys from 1956 to 2007. *Ecology* 91: 1557.

OEH. 2012. National Recovery Plan for the Southern Corroboree Frog, *Pseudophryne corroboree*, and the Northern Corroboree Frog, *Pseudophryne pengilleyi*, Office of Environment and Heritage, NSW, Hurstville.

Osborne WS. 1988. A survey of the distribution and habitats of Corroboree Frogs, *Pseudophryne corroboree* in Kosciusko National Park: with a reference to ski resort development. Report prepared for NSW National Parks and Wildlife Service.

Osborne WS. 1989. Distribution, relative abundance and conservation status of Corroboree Frogs *Pseudophryne corroboree* Moore (Anura: Myobatrachidae). *Australian Wildlife Research*, 6: 537-547.

Osborne WS. 1990. The conservation biology of *Pseudophryne corroboree* Moore (Anura: Myobatrachidae): a study of insular populations. Ph.D. thesis, Australian National University, Canberra.

Osborne WS, Hunter D and Hollis GJ. 1999. Population declines and range contractions in Australian Alpine Frogs. Pp. 145–157 in *Declines and disappearances of Australian frogs.* Ed by A. Campbell. Environment Australia, Canberra.

Osborne WS and Norman 1991. Conservation genetics of Corroboree Frogs, Pseudophryne corroboree: population subdivision and genetic divergence. *Australian Journal of Zoology*. 39:285-297.

Osborne WS, Zentelis RA and Lau M. 1996. Geographical Variation in Corroboree Frogs, Pseudophryne corroboree Moore (Anura: Myobatrachidae): A Reappraisal Supports Recognition of P. pengilleyi Wells and Wellington. Australian Journal of Zoology. 569-587.

Osborne W.S., Hunter, D. and Hollis, G.J. (2000). Population declines and range contractions in Australian Alpine Frogs. Pp 145-157 in *Declines and disappearances of Australian frogs.* Ed by A. Campbell. Environment Australia, Canberra.

Pengilley RK. 1966. The biology of the genus Pseudophryne (Anura: Leptodactylidae). M.Sc. thesis, Australian National University, Canberra.

Pengilley RK. 1971. Calling and associated behaviour of some species of *Pseudophryne* (Anura: Leptodactylidae). *Journal of Zoology*; London, 163: 73-92.

Pengilley RK. 1973. Breeding biology of some species of *Pseudophryne* (Anura: Leptodactylidae) of the Southern Highlands, New South Wales. Australian Zoologist, 18: 15-30.

Pengilley RK. 1992. Natural history of *Pseudophryne* spp. (Anura: Myobatrachidae) in the Southern Highlands of N.S.W., Australia. Sydney Basin Naturalist 1:9-29.

Scheele, BC, Guarino F, Osborne W, Hunter DA, Skerratt LF and Driscoll DA. 2014, Decline and re-expansion of an amphibian with high prevalence of chytrid fungus. *Biological conservation*, 170: 86-91.

Scheele BC, Hunter DA, Banks SC, Pierson JC, Skerratt LF, Webb R. and Driscoll DA. 2016. High adult mortality in disease-challenged frog populations increases vulnerability to drought. *Journal of Animal Ecololgy* 85, 1453–1460.

Scheele BC, Skerratt LF, Grogan LF, Hunter DA, Clemann N, McFadden M, David Newell D, Hoskin CJ, Gillespie GR, Heard GW, Brannelly L, Roberts AA, Berger L. 2017. After the epidemic: Ongoing declines, stabilizations and recoveries in amphibians afflicted by chytridiomycosis. *Biological Conservation*, 206: 37-46.

Skerratt LF, Berger L, Speare R, Cashins S, McDonald KR, Phillott AD, Hines HB and Kenyon N. 2007. Spread of chytridiomycosis has caused the rapid global decline and extinction of frogs. *Ecohealth* 4: 125-134.

Tyler MJ. 1989. *Australian Frogs*. Viking O'Neil, Melbourne.