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The impacts of the 2019–20 wildfires on Australian frogs

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Summary

Context and challenges

- Frogs depend on moist microclimates or burrowing to survive fire.
- The impact of wildfires on frog populations depends on fire severity, and on traits that allow survival and recovery after fire.
- To explore likely indicators of risk to fire, we categorised frog species as occurring in fire-adapted or fire-sensitive vegetation communities; by use of refuge type (burrow, tree hollow, under debris, dense stream side vegetation, permanent wetlands); and by ecological group (breeding in terrestrial sites, ephemeral ponds, permanent ponds and streams and bogs/soaks). We combined this information with estimates of the proportion of species' distributions that overlapped with the 2019–20 wildfires (Legge *et al.* 2022, in press), to consider which species have been most heavily affected. As well as the species considered by Legge *et al.* (in press), we added several species from the south of Western Australia.

Main findings

- Species occurring in fire-adapted vegetation communities use refuges that are more secure against fire, including burrows, tree hollows or under debris. Species in fire-sensitive vegetation communities use refuges (dense shrubs, leaf litter) that are likely to be consumed by fire.
- Range-restricted species that occur in fire-sensitive vegetation have likely suffered the highest impact from the 2019–20 wildfires (e.g. *Assa darlingtoni*, *Litoria kroombitensis*, *L. spenceri*, *Philoria pughi* and *Pseudophryne pengilleyi*).
- Several threatened species with wide but fragmented distributions in fire-adapted vegetation, with high wildfire overlap (*Heleioporus australiacus flavopunctatus*, *L. watsoni* and *L. littlejohni*), were also likely impacted. Early evidence from field monitoring confirms this.

- For most species with broad distributions but not considered threatened, the impacts of wildfire on abundance are largely unknown. We note the value of widespread monitoring using citizen science, e.g. FrogID, in providing information on impacts of major environmental disturbances.
- The short-term effects of wildfire on tadpoles and their aquatic habitats are largely unknown.
- Management and research attention needs to focus on species in fire-sensitive vegetation, and range-restricted species in fire-adapted vegetation communities.

Introduction

The 2019–20 wildfires burnt large areas in eastern and southern Australia (Collins *et al.* 2021). While fires are a common feature in many Australian ecosystems, particularly in eucalypt forests, the extent and severity of the 2019–20 fires was unprecedented (Collins *et al.* 2021). Areas not usually subject to fire also burnt, including significant areas of rainforest; for example, half of the Gondwana Rainforests of Australia World Heritage Area (GRAWHA) burnt (NSW Department of Planning, Industry and Environment 2020; Chapter 4).

Among the affected biota are over 100 species of amphibians, all anurans (frogs) (Legge *et al.* 2022). We consider the impacts of the 2019–20 fires on this group: we (1) summarise what is known generally about the impacts of fire on frogs in Australia, (2) make inferences about fire impacts on species persistence, (3) given these inferences, estimate the impact of the 2019–20 wildfires on frogs, and (4) provide recommendations for research and management of fire-affected species.

Previous studies on the impacts of fire on frogs

Eighteen field studies have investigated the effect of fire on Australian frogs, 11 on low to moderate and seven on severe fires. Most included pre- and post-fire monitoring of abundance (Recher *et al.* 1987; Bamford 1992; Wardell-Johnson *et al.* 1995; Driscoll and Roberts 1997, 1998; Roberts *et al.* 1999; Lemckert 2000; Bamford and Roberts 2003; Lemckert *et al.* 2004; Penman *et al.* 2006; Daly and Craven 2007; Edwards and Roberts 2011; Gillespie and West 2012; Westgate *et al.* 2012, 2018; Lowe *et al.* 2013; Potvin *et al.* 2017; Roberts 2018; Heard *et al.* 2021). Additional studies have used surrogate models to measure heat penetration (Penman *et al.* 2006), fundamental niche models and predicted climate change and fire occurrence (Penman *et al.* 2005b), population genetics (Potvin *et al.* 2017), citizen science involvement (Rowley *et al.* 2020), and two expert elicitations to assess the impact of fire on abundance (Legge *et al.* 2022, in press). Collectively, these studies show that low-severity fires produce minimal or short-term declines in abundance, with several traits (reproductive mode, burrowing) associated with differing sensitivity among species. For example, short-term declines in abundance occurred in *Geocrinia lutea* and *G. vitellina* after their breeding bogs were burnt, with evidence that adults and eggs were killed from heat exposure and desiccation (Driscoll and Roberts 1997). Populations of a congener *G. alba* and another sedentary bog-breeding species (*Spicospina flammocaerulea*) were not affected or abundance increased after fires, at least in the short term (Wardell-Johnson *et al.* 1995; Driscoll and Roberts 1997; Bamford and Roberts 2003; Edwards and Roberts 2011), possibly due to their reliance on secure ground water sources that protect them from radiant heat, and that supported reproduction post-fire.

Five studies of high-severity fires showed strong impacts on abundance. An intense wildfire on the Dorrigo Plateau in mid-eastern New South Wales caused the loss of a small isolated population, and a > 80% decline in a larger isolated population of the litter-dwelling *Assa darlingtoni*, a frog not generally threatened by wildfire since it occurs in temperate rainforests that typically do not burn (Lemckert 2000). In the fire-adapted vegetation community of upland heath, an intense wildfire in the upper Shoalhaven River catchment resulted in declines of adults and tadpoles of *L. littlejohni* (= *L. watsoni*) (Daly and Craven 2007). This is the only study to report impacts on tadpole abundance as well as adults, but it is unknown whether the tadpoles were present in pools and then died from direct fire impacts, or whether few tadpoles were produced because adults sheltering in the riparian zone were killed by fire before breeding. Surveys were conducted in fire-adapted vegetation after the Victorian Black Saturday fires (2009) for three frogs with long-term pre-fire monitoring data. Using standard visual encounter surveys, the abundances of two pond breeding tree frogs (*Litoria ewingi* and *L. paraewingi*) were not significantly different pre- and post-fire. However, using molecular genetic methods, it was found that there was a marked reduction in effective population size and genetic diversity (Potvin *et al*. 2017). In *L. spenceri*, a stream-breeding species, juvenile recruitment was lower immediately post-fire, but adult survivorship increased compared with before-fire estimates (Gillespie and West 2012).

Following the extensive fires of 2019–20, a rapid assessment was undertaken to prioritise species for management intervention (Legge *et al*. 2022). Assessment focussed on nationally and globally threatened species (*Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and IUCN Red List) plus additional species that experts considered to be at risk. A risk score was calculated for each species from the pre-fire imperilment and extent of fire overlap, and a set of traits was used to estimate variability in mortality. Risk score and trait variability were combined to identify species with highest priority for urgent management intervention. Twenty-four threatened species had > 10% of their distribution fire-affected and a further 11 unlisted species had > 30% fire overlap. A subsequent analysis used expert elicitation to estimate population loss and recovery for 66 frog taxa (with > 10% fire overlap) (Legge *et al*. in press). This assessment predicted that six frog taxa would experience > 30% decline 10 years/three generations after the fire. Coupled with other parameters of extinction risk, seven taxa were considered eligible for up-listing of threatened status, and eight for threatened species listing.

Inferring fire impacts on frogs

The distribution and abundance of frogs is determined by the availability of water in the environment (Hillman *et al*. 2008). Frogs do not drink, absorbing water through their skin and losing it by evaporation. Frogs must find moisture in the environment to maintain water balance (e.g. ponds, streams, wet soil, damp leaf litter, condensation). In humid environments, water loss from the skin and lungs is limited, but in dry conditions it is high and frogs use a range of adaptations to avoid desiccation, typically moving to protective microhabitats (Tracy *et al*. 2011). The greatest threat to their survival is dry air and a dry environment; both become prevalent during drought and wildfire events. In wildfires, radiant heat kills exposed individuals and destroys protective habitats, and the aftermath is a dry landscape that threatens survival. Frogs are small, have low mobility, constantly rely on moisture, and their life cycles are tied to terrestrial and aquatic habitats that are impacted by fire in different ways. Yet they occur in fire-adapted vegetation communities, so they must have specific adaptive traits that enable them to survive fire.

Fire has long been a component of eucalypt and heath ecosystems, both fire-adapted vegetation communities; but rainforest, without a history of fire, is fire sensitive (Hardesty *et al*. 2005). Most Australian frogs occur in fire-adapted vegetation, and have behavioural adaptations to avoid temperature and moisture stress, that may also protect them from wildfire. For example, arboreal tree frogs shelter in hollows or under bark; those that stay closer to ground may shelter in dense vegetation, in reed beds or under debris (Lowe *et al*. 2013; Mo 2015). Most ground frogs shelter by burrowing, moving under debris, into deep soil cracks, or into reed beds (Bamford and Roberts 2003). In fire-sensitive communities, where fire is normally excluded because of the high moisture content in soil, leaf litter and plants, frogs are presumably not adapted to wildfire, but their response is unknown because wildfires have not previously occurred in these habitats (Collins *et al*. 2021).

The 2019–20 wildfires

Thirty-eight frog species occur in, with 11 species restricted to, relictual temperate and subtropical rainforest of the GRAWHA. This area represents the second highest level of phylogenetic endemism for Australian frogs (Rosauer *et al*. 2009). About 53% of this area burnt in the 2019–20 wildfires (NSW Department of Planning 2020).

We aimed to understand the reliance that frogs have on specific habitat features, mostly refuges, in order to help identify actions and research needs for fire-impacted frogs. We considered those frog species whose distributions overlapped with the 2019–20 fires. We used our collective experience to categorise their dependence on fire-sensitive and fire-adapted vegetation communities. Fire-sensitive communities are 'vegetation communities that have no history of fire' (Hardesty *et al*. 2005), including rainforest and permanent coastal wetlands. Wet sclerophyll vegetation is fire-adapted but with a very long return interval. We considered traits that could provide protection from fire and enable population recovery, including refuge site and breeding mode (ecological group). Full details on the taxa covered, their vegetation community category and refuge sites are available in Supplementary Table S13 online at doi:10.6084/m9.figshare.20132186. We follow Legge *et al*. (in press) for estimates of fire overlap, and also by considering fire impacts on species and on subspecies when they were differentially impacted by fire, and using 'taxa' when referring to a mix of species and subspecies, and 'species' when referring only to that taxonomic rank. Our analysis is also informed by several unpublished monitoring projects on frog occupancy undertaken since the 2019–20 wildfires.

Findings

Occurrence in fire-sensitive and fire-adapted vegetation communities

Most frog species in our analysis occur in fire-adapted vegetation communities (92 of 103 species), with only 12 restricted to fire-sensitive communities (Table 13.1). Six species of frogs from fire-sensitive vegetation communities were listed as threatened at the time of the 2019–20 wildfires (*Mixophyes fleayi*, *Philoria frosti*, *P. kundagungan*, *P. richmondensis*, *P. sphagnicolus*, *Taudactylus pleione*). A further two (*Assa wollumbin*, *Philoria knowlesi*) have been recognised since then, with application of the IUCN Red List criteria (IUCN 2019) indicating they should be listed as threatened (Mahony *et al*. 2020, 2021). Monitoring of *P. richmondensis*, *P. kundagungan* and *P. knowlesi* (pre- and post-fire) has revealed lower abundances at burnt sites (Heard *et al*. 2021). Changes in habitat structure due to loss of

Table 13.1. Dependence on fire-adapted vegetation communities (percentage classes) against the proportion of their distributions that overlapped with the 2019–20 fires, for 103 species of frogs.

Within wildfire overlap categories the table is presented with taxa arranged in families, Limnodynastidae, Myobatachidae and Pelodryadidae. The table is presented in a risk assessment format such that the species with the highest level of fire overlap (> 60% of distribution), which also depend on fire-adapted vegetation communities, are highlighted in red, and those with moderate overlap (> 40%) in orange. Threatened species (EPBC Act and IUCN Red List) are highlighted in bold.

	Dependence on fire-adapted vegetation communities				
Wildfire overlap	**≤ 20**	**21 ≤ 40%**	**41 ≤ 60%**	**61 ≤ 80%**	**81 ≤ 100%**
0–20%	*Philoria frosti, P. loveridgei, P. richmondensis*[b]				*Heleioporus albopuncatatus, H. psammophilus, Limnodynastes convexiusculus, Lim. dumerili dumerilii, Lim. d variagatus, Lim. peronii, Lim. salmini, Lim. tasmaniensis, Neobatrachus albipes, Platyplectron ornatus.*
	Assa darlingtoni, ***A. wollumbin, Mixophyes fleayi, Taudactylus pleione***	***Mixophyes iteratus***			*Crinia georgiana, C deserticola, C. parinsignifera, C. signifiera, C. tinnula, Myobatrachus gouldii, Pseudophryne australia, P. biboroni*[c]*, P. major, P. semimarmorata,* **Uperoleia mahonyi,** *U. martini, U. rugosa*
			Litoria brevipalmata, ***Litoria kroombitensis***[a]	*L. wilcoxi*	*Cyclorana albogutatta, C. brevipes, Litoria moorei/cyclorhyncha*[d]**, *L. castanea, L. raniformis***, *L. fallax, L. caerulea, L. ewingi, L. verreauxi, L. inermis, L. latopalmata, L. nasuta, L. peronii, L. rothii, L. belatus, L. rubella*
21–40%	*Lechriodus fletcheri, Philoria kundagungan*	*Litoria pearsoniana*		*A. brevis*	*Lim. dumerilii insularis*
				Geocrinia victoriana, Paracrinia haswelli, Pseudophryne coriacea, P. corroboree	*Crinia pseudinsignifera, C. subinsignifera, Metacrinia nichollsi*[b]*, Pseudophryne raveni, Uperoleia fusca, U. laevigata, U. tyleri*
			Litoria aurea[b]*, L. barringtonensis, L. chloris, L. nudidigita, L. revelata*	*Litoria cooloolensis, L. booroolongensis, L. lesueuri,*	***Litoria olongburensis****, L. gracilenta,* ***L. piperata****, L. jervisiensis, L. freycineti, L. tyleri, L. quiritatus*

continued

Table 13.1. Continued

Wildfire overlap	Dependence on fire-adapted vegetation communities				
	≤ 20	21 ≤ 40%	41 ≤ 60%	61 ≤ 80%	81 ≤ 100%
41–60%	***Philoria knowlesi***				*Heleioporus a. australiacus*
		Mixophyes balbus, *M. fasciolatus*		***P. pengilleyi***	
			Litoria phyllochroa		*Litoria spenceri*
61–80%	*Philoria sphagicolus*			*L. citropa*	*Limnodynastes d. fryi, L. d. grayi*
		Litoria daviesae	*Litoria subglandulosa*		***Litoria littlejohni****, L. dentata, L. belatus, L. quiritatus*
81–100%	*Philoria pughi*				***Heleioporus a. flavopunctatus***
					Litoria watsoni

[a] Unaffected by 2019–20 wildfire but affected by 2018 wildfire.
[b] Genetically distinct population in the Stirling Ranges (Edwards *et al.* 2008)
[c] Species occurs in isolated population on Kangaroo Island, South Australia; > 50% of the island burnt.
[d] Hybrid populations

canopy and streamside vegetation, and feral pig invasion, are likely to cause further drying of critical breeding habitats.

Of 92 species found in fire-adapted habitats, 80 are non-threatened. Wildfires may have reduced their population size (Table 13.2). Sixty species reliant on dense riparian vegetation or leaf litter for protection were most likely affected (Table 13.3). Unplanned monitoring of these species has occurred through FrogID (Rowley *et al.* 2020), and numerous species persist (Box 13.1); however, the extent of impact is not known. The highest impacts were probably experienced by the 12 threatened taxa that occupy fire-adapted communities, notably the ground frogs *Pseudophryne corroboree*, *P. pengilleyi* and *Mixophyes balbus*, and tree frogs *Litoria daviesae*, *L. littlejohni*, *L. piperata*, *L. spenceri* and *L. watsoni* (Table 13.1).

Box 13.1. The value of citizen science in understanding the impact of fire on frogs

In the wake of the 2019–20 wildfires, there was an urgent need to understand the impacts on frogs, and subsequent conservation priorities. The enormous logistical challenges involved in rapidly collecting post-fire data across a large geographic area were further compounded by COVID-19 travel restrictions. However, the national citizen science project, FrogID (Rowley *et al.* 2019), gathered data on calling frog records across the fire zone, providing the first published data on the persistence of frogs through the fires (Fig. 13.1; Rowley *et al.* 2020). This study demonstrated

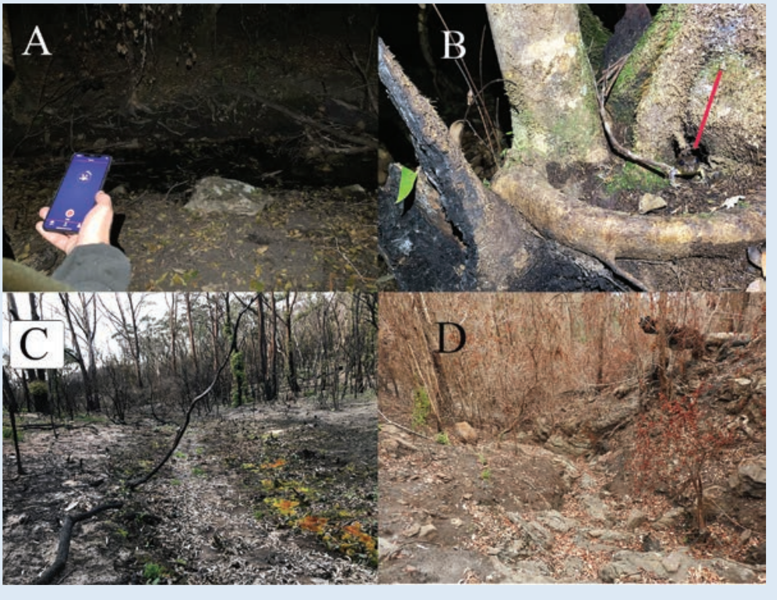

Fig. 13.1. (A) Use of smartphone with the FrogID application to record frog calls; (B) *Mixophyes balbus* (arrow) at entrance of refuge hollow in base of partly burnt rainforest tree, Gibraltar Range National Park, NSW; (C) burnt peat swamp, breeding habitat of *H. a. australiacus*, Newnes Plateau, NSW; and (D) burnt upland rainforest, stream habitat of *P. kundagungan*, Main Range National Park, Qld. (Photos: (A, B) J. Rowley, (C) M. Mahony, (D) H. Hines)

widespread short-term persistence of frog species, with 45 frog species detected within 125 days post-fire. All 33 frog species with more than five records from the months of December–March pre-fire were detected post-fire. As the FrogID database grows, the longer-term impacts of the fires can be assessed, and the database now holds over 10 000 records of over 100 frog species from areas burnt in the 2019–20 wildfires. While most of these records are of common, widespread species of low conservation concern (i.e. 17% *C. signifera*), they also include threatened species and species of conservation concern post-fire (e.g. *A. wollumbin*, *P. pughi*). Alongside traditional scientific monitoring, citizen science projects such as FrogID offer a powerful new tool to understand the impact of fires on Australia's biodiversity, while also engaging the public in biodiversity monitoring.

Table 13.2. Habitat refuges used by frogs during wildfire.

Only species within the fire-overlap zone are included. Arranged by family (Limnodynastidae, Myobatrachidae and Pelodryadidae in separate rows) and genera with number of species in brackets.

Protective refuge	Number of species	Families	Genera and species
Burrows	21	All ground frogs, Myobatrachidae and Limnodynastidae. Some tree frogs, Pelodryadidae	*Heleioporus* (5), *Limnodynastes* (4 sp., 6 taxa), *Myobatrachus* (1), *Neobatrachus* (1), *Philoria* (1), *Platyplectron* (1)
			Mixophyes (4), *Myobatrachus* (1), *Taudactylus* (1)
			Cyclorana (2)
Hollows	11	All tree frogs, Pelodryadidae	*Litoria* (11)
Under debris on ground, under or between rocks	47	Approximately equal number of ground and tree frogs	*Adelotus* (1), *Limnodynastes* (4)
			Crinia (5), *Metacrinia* (1), *Pseudophryne* (8), *Uperoleia* (5)
			Litoria lesueuri sp. group (3)*, *Litoria* (20)
Leaf litter	12	All ground frogs	*Philoria* (5), *Lechriodus* (1)
			Assa (2), *Geocrinia* (1), *Paracrinia* (1), *Pseudophryne* (1), *Uperoleia* (1)
Dense streamside vegetation	7	All tree frogs, Pelodryadidae	*Litoria* (7)
Within wetland	6	One ground frog Myobatrachidae and 5 tree frogs, Pelodryadidae	*Crinia* (1)
			Litoria (5)
Total number of species	104		

* Species groups are from Tyler and Davies (1978)

Table 13.3. Numbers of species in ecological groups (after Murray *et al.* 2011) and occurrence in fire-adapted or fire-sensitive vegetation communities.

Species and taxa with tadpoles that are not free-living or have direct development are in bold, all others have free-living tadpoles.

Ecological group	Total number of species or taxa	Highly dependent on fire-sensitive vegetation community. Number of species or taxa	Highly dependent on fire-adapted vegetation community. Number of species or taxa
Terrestrial breeders	22	***Philoria* (7), *Assa* (2), *Geocrinia* (1), *Metacrinia* (1), *Myobatrachus* (1),** *Pseudophryne* (9), *Taudactylus* (1)	
Ephemeral water bodies	34	*Lechriodus* (1)	*Heleioporus* (4), *Limnodynastes* (3), *Neobatrachus* (1), *Platyplectron* (1), *Crinia* (5), *Uperoleia* (5), *Cyclorana* (2), *L. brevipalmata* (1), *L. caerulae* sp. group (3), *L. rubella* sp. group (4), *L. latopalmata* sp. group (4)
Permanent water bodies (ponds and wetlands)	28		*Adelotus* (1), *Limnodynastes dumerilli* (5), *Lim. peronii* (1), *Lim. terrareginae* (1), *Crinia tinnula* (1), *C. parinsignifera* (1), *Paracrinia* (1), *Uperoleia tyleri* (1), *Spicospina* (1), *Litoria adelaidensis* (1), *Litoria aurea* sp. group (4), *L. fallax* sp. group (3), *L. ewingi* sp. group (4), *L. peronii* sp. group (3)
Streams	17	*Mixophyes* (4)	*L. phyllochroa* sp. group (10), *L. lesueuri* sp. group (3)

Importance of refuges

More than 78 frog species shelter in refuges that likely provide thermal and moisture protection from wildfire (Table 13.2). Forty-seven taxa shelter under terrestrial debris: decaying logs and rocks with crevices for a frog to squeeze under where the soil is moist. Twelve forest-dwelling frogs burrow in soil or squeeze into soil cracks (Penman *et al.* 2005a, 2006; Westgate *et al.* 2012). Only 10 species, all tree frogs, rely on arboreal hollows or bark for shelter (Lemckert 1999; Taylor *et al.* 2003; Mo 2015). Field observations show that species found in fire-adapted vegetation and that burrow or move into rock crevices are least affected by wildfire; for example, several taxa appeared on the surface to breed after heavy rainfall that extinguished the fires.

Several taxa shelter in dense riparian vegetation and under leaf litter, and this may make them vulnerable to severe wildfire (Table 13.2). Seven of these occur in fire-adapted vegetation communities (e.g. *L. ewingii* species group) and post-fire monitoring indicates significant impacts on some species (e.g. *L. littlejohni* and *L. watsoni*) (Stock, Wallace and Klop-Toker, unpublished data). Thirteen species that shelter under leaf litter or in the topsoil are also vulnerable to severe wildfire, and several (*Assa* (2), *Philoria* (6), and *Lech. fletcheri*) occur in fire-sensitive vegetation communities (Tables 13.1, 13.2). Where the 2019–20 wildfires penetrated fire-sensitive vegetation communities, post-fire monitoring has indicated a reduction in abundance of *A. darlingtoni*, *P. pughi* and *P. sphagnicolus* (M. Mahony, *pers. obs*.) and *P. knowlesi*, and *P. kundagungan* (Heard *et al*. 2021).

Ecological group

The ecological group of frogs indicates their reliance on landscape topographical features, and thus their vulnerability to severe fires. Forty-five species use permanent streams, ponds, and wetlands for the tadpole stage of the life cycle (Table 13.3); these frogs have a constant source of moisture with cooler, stable temperatures (Driscoll *et al*. 2010; Collins *et al*. 2012; Westgate *et al*. 2018). These habitats are common in fire-adapted vegetation. The fire-caused mortality rate of frogs using these habitats is unknown. Thirty species predominantly inhabit the riparian zones of permanent streams (Table 13.3), and an intense fire in this zone may kill many individuals, especially species that take refuge in leaf litter and understorey vegetation. In some species adults move well away from the riparian zone seasonally to forage, disperse and shelter (Lemckert and Brassil 2000, 2003; Lemckert *et al*. 2006; Newell *et al*. 2013; Quick *et al*. 2015), and if this coincides with intense wildfires, they may be directly exposed, or, protected (e.g. by large boulders). Up to 28 species of frogs breed in permanent ponds and wetlands, mostly in fire-adapted vegetation communities (Table 13.3). While these habitats provide moisture, many frogs that use them shelter in dense surrounding vegetation (tree frogs), in nearby terrestrial refuges (ground frogs), and a small number of species use emergent reed beds. These shelter sites are particularly susceptible to intense fire. Permanent ponds and wetlands may provide protection for tadpoles, but an intense fire in wetland vegetation can lead to the death of many frogs. A wildfire in 2018 burnt through sedges and reeds of permanent wetlands in an estuarine complex on Kooragang Island (NSW) and many individual frogs were observed dead, without any signs of physical burning, apparently killed by heat exposure (M. Mahony, *pers. obs*.).

Thirty-four taxa breed in ephemeral situations (Table 13.3) and these would appear particularly vulnerable to severe wildfire. Most have wide ranges, can be locally abundant, and occupy fire-adapted vegetation, but there is little information on wildfire impact. Several species are arboreal (*L. rubella* sp. group. *L. gracilenta*, *L. brevipalmata*), and crown fires would impact adults. Others are mostly terrestrial (*Crinia* (5), *Limnodynastes* (3), *Uperoleia* (5)) and shelter under debris or in cracks where they may be protected. Post-fire monitoring found *C. signifera* breeding in severely burnt forests once rains occurred (J. Rowley, *pers. obs*.), presumably having been well protected in refuges during the fire.

Twenty-two taxa breed in terrestrial sites (Knowles *et al*. 2004; Willacy *et al*. 2015; Heard *et al*. 2021; Bolitho *et al*. 2021), mostly in fire-sensitive vegetation. Several species of *Geocrinia* in south-western Australia breed in soaks or bogs. One species, *G. vitellina*, which relies on groundwater, recovered well after intense wildfire burnt a large proportion of its habitat in 1997 (Roberts *et al*. 1999). Experimental studies indicate *G. lutea* can cope with low intensity fire but also persists in areas that have been subject to multiple high intensity fires (Bamford and Roberts 2003).

Vegetation preference, refuge types, and ecological group

Of the 12 frog taxa (out of 103 assessed; Table 13.1) that depend on fire-sensitive rainforest and wetland vegetation communities, most do not have traits likely to protect them during wildfire (Tables 13.2, 13.3). *Taudactylus pleione* is the only species known to shelter in rock crevices. Most shelter in leaf litter (*Philoria* (7), *Assa* (2), *Lech. fletcheri* and *M. fleayi*) and would be killed if their habitats burnt. In several of these taxa, larval stages occur underground, depending on ground water to maintain soaks, and are unlikely to be impacted by wildfire. Heard *et al*. (2021) showed a decline in the occupancy and number of calling males of *P. kundagungan* and *P. knowlesi* in areas burnt during 2019–20. Eight of the 12 taxa living in fire-sensitive vegetation are listed as threatened, but fortunately none experienced a high overlap with wildfires (Table 13.1). Wildfires in rainforests pose a great threat, not only because the frog fauna lack adaptations to avoid fire, but because they also have small ranges with derived reproductive modes, and severe wildfires could eliminate small, isolated populations in one event, as recorded by Lemckert (2000).

Threatened species and wildfire

Frogs of conservation concern, listed mostly for threats other than wildfire (Gillespie *et al.* 2020), occurred in fire-sensitive and fire-adapted vegetation communities (Table 13.1). Of most concern among the threatened taxa are 25 that occur in fire-adapted vegetation; several had considerable overlap with the wildfires (Table 13.1), including frogs from montane vegetation communities (*P. corroboree*, *P. pengilleyi*), eucalypt forests (*L. booroolongensis*, *L. daviesae*, *L*, *raniformis*, *L. littlejohni*, *L. spenceri*, *L. watsoni*, *H. a. australiacus*, *H. a. flavopunctatus*, *M. balbus* and *U. martini*) and wallum wetlands (*L. olongburensis*).

Conclusions

Range-restricted species that use fire-sensitive vegetation and shelter in vegetation or leaf litter are likely to have suffered the highest impact from the 2019–20 wildfires (e.g. *Assa* spp., *L. kroombitensis*, *L. spenceri*, *P. pughi*, *Pseud. pengilleyi*). Such species are vulnerable to single wildfire events that can severely reduce abundance and destroy a large percentage of habitat. For threatened species such as *P. pengilleyi*, *T. pleione*, and *L. kroombitensis*, catastrophic events substantially increase the risk of extinction. Several threatened taxa with wide but often fragmented distributions, occurring in fire-adapted communities, had large wildfire overlaps and may also have suffered large losses (*H. a. flavopunctatus*, *L. watsoni*, *L. littlejohni*). Post-fire monitoring has shown persistence of some populations and losses of others, presumably related to differences in local fire severity or drought impacts.

Knowing how frogs will respond to the predicted increase in wildfire occurrence and severity is essential for future management. Previous reviews of fire management for maintaining biodiversity values have focused on fire frequency rather than intensity or severity (Whelan *et al*. 2002; Driscoll *et al*. 2010). Understanding whether frog refuge sites affect their survival in wildfire will indicate which frogs are most vulnerable to fire. This is not to downplay the importance of suitable habitat attributes after the wildfire for supporting population recovery, but we focused here on surviving the fire as the first issue to be understood. Maintaining, protecting, connecting and possibly enhancing habitat refuges could enhance future protection.

Recommendations

To understand and mitigate the impact of future wildfire we recommend:

- For species with restricted or fragmented ranges: map critical habitat on fire management digital layers to inform planned burning and wildfire response. Species of greatest concern: *L. kroombitensis*, *L. littlejohni*, *L. spenceri*, *L. watsoni*, *Assa* spp., *P. corroboree*, *P. pengilleyi*, *Philoria* spp., *T. pleione*.
- For species with large distributions, occurring in fire-adapted vegetation communities and for whom large areas of habitat were destroyed by wildfires: frogs likely survived in

areas that burnt at low–moderate fire severity, and populations are expected to recover over time. This assumption should be verified with monitoring, while habitat is managed to maintain connectivity.

- For all frogs: establish long-term monitoring of representative species using demographic and occupancy approaches (e.g. Bolitho *et al*. 2021), in order to improve our understanding of fire sensitivity. This could be achieved using 'habitat based' groupings of frogs to reduce complexity.
- Undertake rapid assessment of population fitness (fecundity, connectivity and effective population size) using population genetics, to inform conservation actions. While cost-effective, the challenge for this approach is that rapid genetic assessment requires targeted collection and storage of pre-and post-fire samples.
- Support non-invasive citizen science projects (e.g. FrogID), that allow the rapid collection of data on frog species in response to threatening processes across wide spatial scales.
- Undertake research to identify refuges used by frogs and determine how to protect or enhance them.

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