WWF

AUSTRALIA

IMPACTS OF THE UNPRECEDENTED 2019-20 BUSHFIRES ON AUSTRALIAN ANIMALS

NOVEMBER 2020

Acknowledgements

WWF-Australia acknowledges the Traditional Owners of the land on which we work and their continuing connection to their lands, waters, and culture. We pay our respects to Elders – past and present, and their emerging leaders.

WWF-Australia is part of the world's largest conservation network. WWF-Australia has been working to create a world where people live in harmony with nature since 1978.

WWF's mission is to stop the degradation of the Earth's natural environment and to build a future in which humans live in harmony with nature, by conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

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We are grateful to the researchers who provided data or feedback on the report. These include:

- Eddy Cannella
- David Chapple
- Hugh Davies
- Deanna Duffy
- Hugh Ford
- Chris Johnson
- Brad Law
- Sarah Legge
- David Lindenmayer
- Simon McDonald
- Damian Michael
- Harry Moore
- Stewart Nichol
- Alyson Stobo-Wilson
- Reid Tingley
- David Westcott
- John Woinarski

Suggested citation

van Eeden LM, Nimmo D, Mahony M, Herman K, Ehmke G, Driessen J, O'Connor J, Bino G, Taylor M, Dickman CR (2020) Impacts of the unprecedented 2019-2020 bushfires on Australian animals. Report prepared for WWF-Australia, Ultimo NSW

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CONTENTS

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FOREWORD

BY DERMOT O'GORMAN CEO, WWF-AUSTRALIA

In July, WWF released an interim report revealing that nearly 3 billion animals – mammals, birds, reptiles and frogs – were impacted by Australia's bushfire disaster.

That number stunned the world and confirmed that the bushfires were one of the worst wildlife disasters in modern history.

The final report "Impacts of the unprecedented 2019-2020 bushfires on Australian animals" contains new figures that will again shock people.

While the overall estimate that nearly 3 billion animals were in the path of the fires has not changed, scientists have drilled down to reveal the impact on some individual animal species and groupings of species.

It's estimated that nearly 40 million possums and gliders; more than 36 million antechinuses, dunnarts, and other insectivorous marsupials; 5.5 million bettongs, bandicoots, quokkas, and potoroos; 5 million kangaroos and wallabies; 1.1 million wombats; and 114,000 echidnas were impacted.

The report also estimates more than 60,000 koalas killed, injured or affected in some way.

The worst losses were on Kangaroo Island, with more than 40,000 koalas impacted. Next was Victoria with fires scorching forests occupied by 11,000 koalas. But there were also many precious koala populations directly in the path of the fires in NSW, with nearly 8,000 koalas impacted.

That is a devastating number for a species that was already sliding towards extinction in Eastern Australia. We cannot afford to lose koalas on our watch.

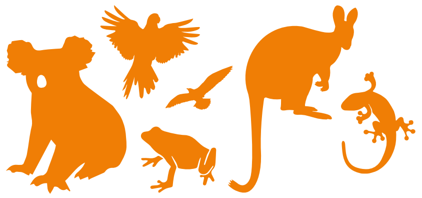
But there is hope. After the bushfire devastation, Australians want to see their nation rebuilt in a way that treasures and protects our unique wildlife.

That's why WWF-Australia has announced Koalas Forever – a bold vision to double the number of koalas in eastern Australia by 2050. Protecting and reconnecting remaining habitat, and restoring forests, can give koalas and dozens of other species the chance to thrive.

Koalas Forever is a key project in WWF's Regenerate Australia plan – the largest and most innovative wildlife and landscape regeneration program in Australia's history.

Under Regenerate Australia, WWF is seeking to raise $300 million program, over 5 years, to help restore wildlife and habitats, rejuvenate communities impacted by the bushfires, boost sustainable agriculture and future-proof our country.

EXECUTIVE SUMMARY



IN TOTAL, WE ESTIMATE THAT THE AREA BURNT IN THE 2019-20 FIRES CONSIDERED HERE WOULD HAVE CONTAINED ALMOST 3 BILLION NATIVE VERTEBRATES.

Over 2019–20, Australia experienced its worst fire season on record in eastern, south-eastern, and parts of south-western Australia.

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More than 15,000 fires occurred across all states, resulting in a combined impact area of up to 19 million hectares (Filkov et al. 2020). Particularly devastating impacts to biodiversity and human life occurred in eastern Australia, with around 12.6 million hectares containing primarily forest and woodland burning (Wintle et al. in press), although these area estimates are contested (Bowman et al. 2020). WWF commissioned us to estimate the number of individual native vertebrates that would have been present within the bushfire impact area and were thus killed or affected as a result of these fires.

In total, we estimate that the area burnt in the 2019-20 fires considered here would have contained almost **3 billion** native vertebrates. These comprise approximately:

- 143 million mammals
- 2.46 billion reptiles
- 181 million birds
- 51 million frogs

Estimates of impacts to reptiles are substantially higher than for the other vertebrate taxa considered. This is because densities of reptiles can be much higher than what is typical for other taxa, with some species (e.g., small lizards such as skinks) reaching densities of over 1,800 individuals per hectare. Indeed, among the top 20 most numerous reptile species in our estimates, 16 are skinks.

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METHODS AND LIMITATIONS

We defined the study area to comprise 11.46 million hectares. This area is primarily in the southeast and southwest of Australia, along with 120,000 hectares of rainforest vegetation in northern Australia. This area excludes vegetation types such as savannah in northern Australia that commonly burn, thus limiting the study area to fires that were largely considered uncharacteristic in intensity and extent.

The methods used to develop the numerical estimates vary between taxon groups, largely due to inconsistency in the extent and availability of the data. At a broad level, these methods were:

- **Mammals:** For most groups, a literature review was conducted to collect available data on the densities of different mammal species. These estimates were categorised into 11 species groups and then averaged per group for each of the fire-affected bioregions to develop population counts per hectare within the fire impact area.
- **Reptiles:** A modelling approach was taken that predicted squamate reptile densities in a given location as a function of broad-scale environmental variables combined with species body size. The model was informed by a global database of reptile densities that included some density estimates from Australia.
- **Birds:** Estimates were derived from BirdLife Australia's Birdata database. Almost 104,000 standardised surveys of bird counts were included in the analysis, stratified by vegetation type and bioregion.
- **Frogs:** The distribution of 67 frog species was mapped to stream and non-stream (including wetland) habitats. Density of frogs in these habitats was estimated based on literature and expert knowledge. Mapped distributions were overlaid on the fire footprint, and the number of frogs assumed to be within the fire impact area calculated.

Major taxonomic groups with insufficient data on densities could not be included in the analysis (e.g., invertebrates, fish, turtles). All methodological approaches come with limitations that affect the accuracy of the calculations, and as such, approaches were taken that sought to be conservative.

Our data do not directly estimate numbers of individuals killed because our understanding of the factors influencing mortality of different taxa is also limited. There are several key factors that are likely to affect mortality, including:

DIRECT FACTORS

- species' ability to flee or shelter from fire,
- varying fire behaviour (e.g., fire intensity),
- availability of suitable habitat, including unburnt refuges,
- smoke inhalation, and
- heat stress and associated stresses from trauma, injury and dehydration.

INDIRECT FACTORS

- runoff of sediment into waterways,
- decreased availability of, and competition for, resources, and
- increased predation risk.

There are, in addition, anthropogenic factors at play in the immediate post-fire environment such as salvage logging and 'clean up' operations in burnt forest or clearing of unburnt vegetation from previously approved development applications.

CONCLUSION AND RECOMMENDATIONS

Our estimate of nearly 3 billion animals impacted by the bushfires is almost three times as large as the original estimate of over 1 billion animals made by Chris Dickman in January 2020 (Dickman & McDonald 2020). At the time, Professor Dickman noted that the estimates were highly conservative and didn't include some groups such as frogs or bats. The fires continued in the months of February and March.

It is important to note that we estimated the number of animals that may have been present within the areas burnt by the 2019-20 bushfires. Even if resident animals were not killed outright by fires and managed to escape, they will surely have experienced higher subsequent risk of death as a result of injuries or later stress and deprivation of key resources.

Some of the factors that limit our ability to accurately estimate the impacts of the bushfires, including mortality, are:

- Limited data on animal densities
- Limited data on the variable impacts of fire and of different species' ability to survive fire (see above)
- Interaction between the impacts of fire and other threats that affect species' ability to survive and recover (e.g., predators are often better able to hunt after fire, fires may encourage invasive animals and plants, or fire may trigger further habitat destruction by logging or clearing).

Based on our assessment and our observations of the limitations of these numerical estimates, we make recommendations to improve monitoring, fauna recovery, and management of future bushfires and their impacts on biodiversity. Thus:

To better understand the impacts of bushfires:

- Adequately fund and implement appropriate long-term monitoring in all bioregions that are likely to be at risk in future bushfires
- Identify and map the distributions of biota that are likely to be most at risk in future bushfires
- Identify key populations and communities of fire-susceptible species, and areas where populations of such entities co-occur, and develop and implement strategies to reduce the risk of extensive, high-intensity fires in these areas (and protect such areas during operations to control fire)
- Identify key resources (e.g., food, water, shelter, protection from introduced predators or competitors) that are required by these species to maintain their populations and persist after bushfire
- Experimentally evaluate the effectiveness of different post-fire management actions that aim to ensure the persistence, and recovery, of fire-susceptible species and communities; and implement effective recovery actions
- Develop standard national methodologies for surveying and modelling animal densities across all taxon groups (which may differ for different taxa).

To mitigate bushfire impacts on biota and appropriately manage risk:

- Improve habitat connectivity to ensure access to fire refuges
- Identify and protect unburnt habitat that is critical habitat for threatened species recovery and build fire recovery into species Recovery Plans and Conservation Advices for species listed as nationally threatened under the EPBC Act
- Establish improved fire prevention and management practices, drawing from traditional ecological knowledge where possible and appropriate to do so
- Establish rapid response teams that will act to assess and mitigate impacts on threatened species and ecosystems when fires occur, using both in situ and ex situ (e.g., wildlife rescue) approaches, as appropriate.

Reduce post-fire impacts on species such as elevated predation, herbivory, clearing, salvage logging, removal of logs, dead wood and other structures that provide shelter to fire-survivors.

1. BACKGROUND

1.1. FIRE IN AUSTRALIA

Australian landscapes have evolved with fire, and many plant and animal species have adapted to survive, benefit from, and even depend on fire. Australia's First Nations Peoples have used fire to carefully manage landscapes, a tool which both provides natural resources and can also help prevent catastrophic wildfire.

However, over the last several decades, fire extent, frequency, and intensity have increased due to warming global temperatures, reduced rainfall in many areas and increased interannual variance in weather conditions. Correspondingly, the detrimental impacts of fire on biodiversity have increased (Lindenmayer & Taylor 2020).

In Australia, the probability of extreme fire risk is predicted to increase by 25% by 2050 and by a further 20% by 2100, even if trends in greenhouse gas emissions are estimated conservatively (Pitman et al. 2007). Understanding the impacts of changing fire regimes, including major fire events, is necessary to manage impacts on biodiversity and ecosystems.

1.2. THE 2019-20 BUSHFIRE SEASON

Australia experienced an unprecedentedly prolonged, extensive and severe season of wildfires between June 2019 and February 2020. This season has been referred to variously as the 'Black Summer' and the 'season from hell' (Davey & Sarre 2020; Woinarski et al. 2020a). In Australia, 2019 was the hottest and driest year on record and the accumulated Forest Fire Danger Index (FFDI), a measure of the degree of fire danger in Australian forests, was the highest on record for spring 2019 over large areas of the continent (Fig 1, Filkov et al. 2020). More than 15,000 fires occurred across all states, resulting in a combined total impact area of up to 19 million hectares, including all vegetation and land use types (Filkov et al. 2020). Around 12.6 million hectares burned in eastern and south-eastern Australia (Wintle et al. in press), primarily in forest and woodland, along with additional areas in the southwest and north of the continent that included grassland and savanna. While fires are an annual occurrence in many Australian ecosystems

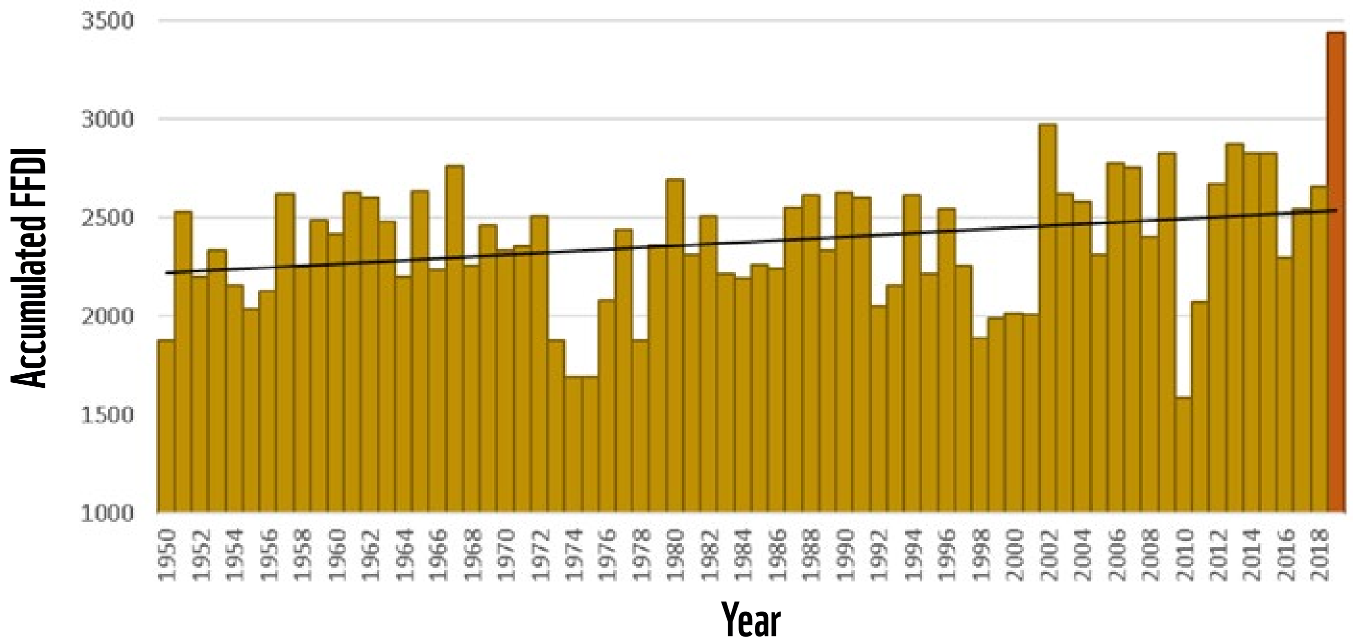

Figure 1: Accumulated Forest Fire Danger Index (FFDI) for Spring from 1950 to 2019. Figure from Bureau of Meteorology in Filkov et al. (2020).

such as the northern tropical savannahs, some burned areas include vegetation types like rainforest that rarely experience bushfire.

The 2019-20 fires had devastating impacts on the people who live in these regions, resulting in 33 human fatalities and more than 3,113 homes burned (Filkov et al. 2020). The smoke from the fires also affected millions of people living far from these areas, with cities like Sydney and Canberra experiencing hazardous air pollution levels, and smoke even reaching the skies over New Zealand (Filkov et al. 2020). An estimate of more than 400 deaths, 1100 hospitalisations for cardiovascular problems and 2000 for respiratory problems, and 1300 presentations to emergency departments for asthma are attributed to the smoke between October 2019 and February 2020 (Borchers Arriagada et al. in press).

The 2019-20 fires also released 900 million tonnes of carbon dioxide emissions (see Filkov et al. 2020).

The Australian government, through the work of its Wildlife and Threatened Species Bushfire Recovery Expert Panel, released a preliminary estimate of the impacts of the bushfires on threatened species, ecological communities, and World Heritage Areas (DAWE 2020). The panel estimated that 49 threatened species had lost more than 80% of their modelled habitat, a further 65 have lost more than 50%, and a further 77 have lost more than 30% of their modelled habitat. For threatened ecological communities, the panel estimated that four had more than 50% of their distribution within the mapped fire extent and a further three had more than 30% of their distribution within the mapped fire extent. The panel estimated that the fires affected significant proportions of at least three World Heritage Sites, including 54% of the Gondwana Rainforests of Australia (Queensland and New South Wales), 81% of the Greater Blue Mountains Area (NSW), and 99% of Old Great North Road (an Australian Convict Site in NSW). Further modelling by Ward et al. (2020) indicated that the 2019-20 fires burnt habitat for 832 species of native vertebrates, including threatened and nominally non-threatened species.

DAWE also established a methodological framework for consistent on-ground assessments of the impacts of the bushfires on fauna, but until field data are collected, assessments of the impacts of the fires are limited to expert judgements and estimates based on data from past fire events.

The estimates of proportional overlap of distributions of species (and ecological communities and World Heritage sites) with fire made by DAWE (2020) provide insight into the conservation consequences of the fires, but may not reveal the full picture of the impacts of the fires on wild animals. With such a large area of the continent severely burnt, Professor Chris Dickman considered the impacts of the fires on individual animals, estimating that more than 1 billion vertebrate animals were likely to have been killed by the fires (Dickman & McDonald 2020).

1.3. SCOPE OF THIS STUDY

This study aims to improve our understanding of the impacts of the 2019-20 bushfires on native Australian vertebrates. Specifically, we seek to estimate the number of individual animals impacted by the fires, refining Dickman's initial estimate of over 1 billion animals in January 2020 (Dickman & McDonald 2020), and providing a framework that would allow more rapid assessment of the effects of any large-scale disturbance events in the future.

Dickman's estimate was based on the method of Johnson et al. (2007), which entailed multiplying areas of habitat destroyed by vertebrate animal density estimates that were available at the time.

In this study, we follow the same approach but incorporate more recent data on known wildlife densities. It was beyond the scope of this study to conduct field assessments to determine actual densities or other important demographic attributes such as the mortality rates of different taxa. Instead, we focused on updating data on population densities, or on modelling densities where field data were scant or unavailable.

While the study aims to estimate the number of individual vertebrate animals living in the footprint of the fires, this is not necessarily the same as animal fatalities. This is because different factors affect the likelihood that animals will survive or perish in the fires. For example:

- *Animal life history*: Some animals are better adapted to surviving fire than others. Highly mobile animals, adult birds in particular (but not nestlings), may be able to flee the fire and survive (at least temporarily) in other areas; others such as wombats may be able to escape (at least while the fires burn) into deep burrows, and small reptiles and small mammals may be able to shelter below ground, in rock crevices or in other fire-refuges (Banks et al. 2011; Stawski et al. 2015).
- *Animal morphology and physiology*: If animals survive a fire, they must then contend with the post-fire environment and its depleted resources. Some marsupials can temporarily reduce their metabolic demands by entering torpor (Stawski et al. 2015), while others such as the echidna can access deeply buried food resources, such as ants and termites that survive fires in their underground nests and galleries. Species such as the echidna may also be less susceptible to predation in the post-fire environment owing to their sharp spiny coats.
- *Landscape features*: The ability of animals to survive fire may be contingent on the landscape they are located within. Animals may have a higher chance of survival in areas where fire impacts were patchy, such as where there are wet microcosms created by gullies or waterways (Lindenmayer et al. 2008; Chia et al. 2015).
- *Local habitat features*: Habitat features such as tree hollows can sometimes provide refuge for fauna from some fires (Banks et al. 2011), as can large rocks, rockpiles and caves if these are present.
- *Fire severity and intensity*: Linked with landscape and local habitat features, differing fire intensities may allow different kinds of wildlife to survive. For example, if the crowns of trees are not burnt, some animals may escape by taking refuge there. Fire intensity mapping was not consistently available at the time that this study was conducted (but has since been made available nationwide).

Even if individual animals are not killed directly by fires, many do not have the adaptations noted above and are likely to be negatively impacted by reduced availability of food and shelter. This will result in increased competition with other species and, with the loss of cover, also increase the risk of predation by species like introduced domestic cats (Felis catus) and red foxes (Vulpes vulpes) (Sutherland & Dickman 1999; McGregor et al. 2014). Fire can also negatively affect fauna in unburnt areas due to influxes of animals escaping burns in neighbouring areas (Lindenmayer et al. 2013), as well as to the movement of ash and sediment into rivers and creeks. Unburnt refuge areas may also be too small to retain populations of species with large home range requirements. Additional effects likely arise from smoke pollution extending from burnt to unburnt areas, although the magnitude of such effects has been little studied. There is also potential for disruption to movement patterns and reproductive opportunities for migratory species. For example, birds that migrate to east coast woodland areas may have missed a breeding season owing to the lack of habitat and food resources in the wake of the fires.

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ACTUAL IMPACTS OF THE BUSHFIRES ON FAUNA

While it was beyond the scope of this study to conduct field assessments, some such assessments have occurred since the fires, reporting on localised impacts to wildlife. In March 2020, Eco Logical Australia conducted surveys in Gibraltar Range National Park and Torrington State Conservation Area in north-eastern New South Wales, following fires in November 2019 (Eco Logical Australia 2020). All seven sites assessed had lost all lower ground vegetation while the canopy remained intact in some places. Burned vegetation included rainforest areas which would not normally be affected by fires, indicating a severe fire event. Based on aural/visual diurnal transect searches (60 minutes each) and baited camera traps (16–17 nights), Eco Logical estimated a reduction of more than 90% in the fauna that could have been expected to be seen, with only highly mobile species such as kangaroos and wallabies recorded regularly. There were almost no low-mobility, ground-dwelling species recorded, with only two small ground mammal and five small reptiles observed. Birds that would usually be common on the ground in the area (e.g., quail-thrush and scrubwrens) were not detected. The study concluded that smaller and relatively immobile species were likely to have been seriously affected, while larger and more mobile species could flee the area and return.

1.3.1. TAXA INCLUDED

Due to limitations on availability of data for species densities, the faunal groups included in this report are:

- Terrestrial mammals including bats
- Squamate reptiles
- Birds
- Frogs

Because of differences in the ecology, life histories and availability of data for these groups, the methods used to estimate the number of individuals impacted differ for each group, and these methods are explained in more detail in each section of the report.

The above list necessarily excludes large groups of fauna for which no adequate density estimates exist or for which impacts are indirect and thus difficult to quantify. These include:

- **Aquatic vertebrates (fish and non-squamate reptiles) and aquatic invertebrates.** The bushfires will have had negative impacts on these groups directly, but aquatic habitats are also likely to have been further affected in catchments where heavy rains following fire-washed ash and other sediments into the waterways, polluting burnt areas as well as downstream areas outside the immediate fire-impact zones. Indeed, the recent federal government assessment identified 22 threatened crayfish species, and 16 threatened freshwater fish that are most at increased risk of extinction as a consequence of the 2019-20 bushfires (DAWE 2020).
- **Terrestrial invertebrates.** Despite representing the majority of animal species (Chapman 2009), data on population densities of invertebrates are lacking in Australia. In January 2020, based on estimates of arthropod densities in ecosystems overseas, Dr Chris Reid estimated that up to 240 trillion arthropods were likely to have been impacted over an area of 8 million hectares burned (C. Reid, Australian Museum, pers comm. 8/7/2020). Since those estimates were made, a further 4 million hectares of vegetation burnt. As such, this number will have increased still further. Similarly, Professor Mike Lee estimated that at least 700 insect species might have been driven to extinction as a result of the fires (Lee 2020). These two estimates consider only a subgroup of invertebrates (e.g., they exclude annelids, nematodes, turbellarians, etc.). Such estimates are of course subject to many assumptions and represent extrapolations in some cases using small initial datasets, but nonetheless serve as reminders that the 2019-20 bushfires affected much more than the vertebrate taxa that form the main focus of our report.

We trust that field research following the fires, alongside the resumption or establishment of robust long-term ecological monitoring, can help to address some of these knowledge gaps so that more comprehensive estimates of fire impacts, and predictions about future impacts, can be made.

1.3.2. STUDY AREA

We used the National Indicative Aggregated Fire Extent Dataset (NIAFED, Feb 2020 release) to define the impact area for the burns (Environmental Resources Information Network 2020). This impact area excludes fires in the 2019-20 season in regions where fires are not considered unusual; for example, the savannah and grassland ecosystems of northern and central Australia. We use this NIAFED impact area, but also include 120,000 ha of rainforest burnt in northern Australia (as mapped by the National Vegetation Information Systems' [NVIS] Extant Major vegetation Groups version 5.1) where more than 500 ha of these vegetation types had burnt, on the basis that fire in these ecosystems is also highly unusual. The resulting focus area totals 11.46 million ha (Table 1, Figure 2).

In addition to fire mapping, we used Interim Biogeographic Regionalisation for Australia (IBRA) mapping to provide finer scale resolution of animal densities and areas burnt for taxon groups where data were sufficient to allow this. IBRA version 5.1 was used, with our analyses focused at the scale of bioregions (see: https://www.environment.gov.au/land/nrs/science/ibra).

We derived estimates for mammals, reptiles, and birds from the whole study area. The estimates for frogs were limited to Victoria and New South Wales due to limitations on available data elsewhere.

STATE	AREA BURNT (HA)
AUSTRALIAN CAPITAL TERRITORY (ACT)	74,000
NEW SOUTH WALES (NSW)	6,897,000
NORTHERN TERRITORY (NT)	35,000
QUEENSLAND (QLD)	619,000
SOUTH AUSTRALIA (SA)	338,000
TASMANIA (TAS)	43,000
VICTORIA (VIC)	1,888,000
WESTERN AUSTRALIA (WA)	1,569,000
TOTAL	11,463,000

Table 1: Total area burnt in the 2019–2020 bushfire season in each state (in hectares) included in this analysis (derived from Environmental Resources Information Network 2020).

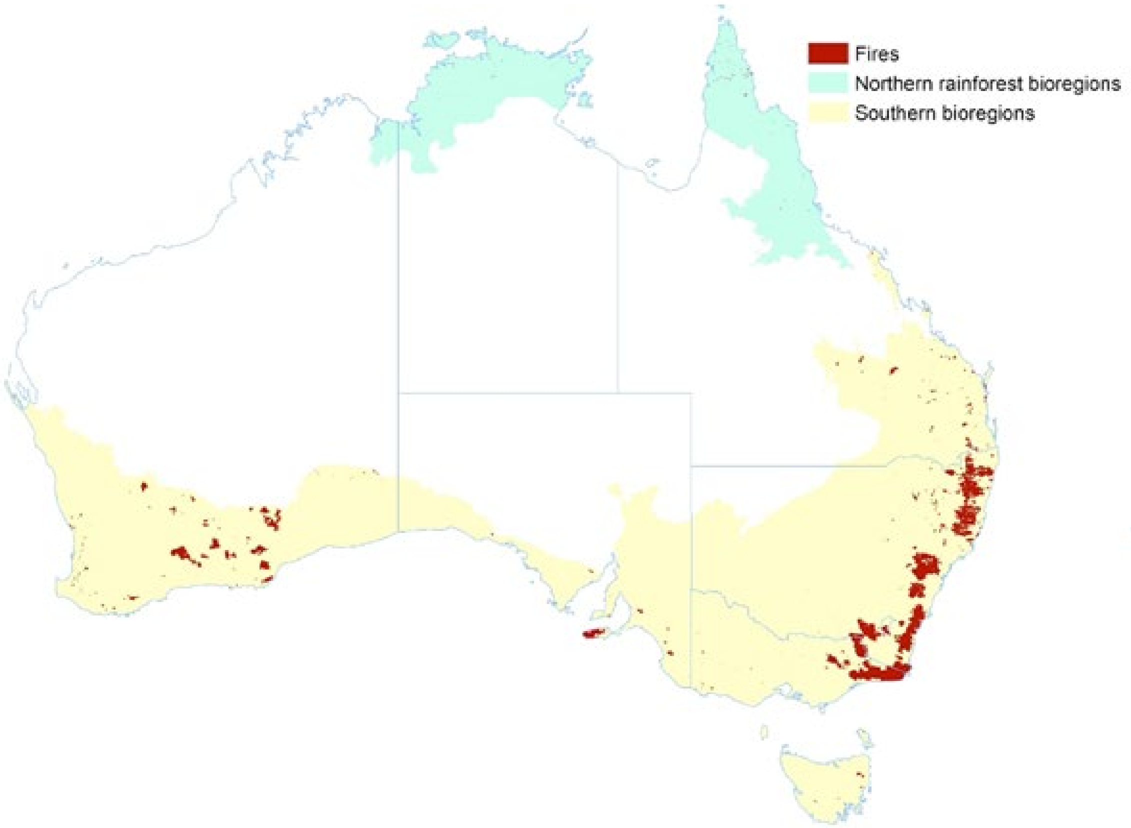

Figure 2: Study area, indicating extent of burned habitat included in this report. Yellow and blue shading indicates bioregions (IBRA) included in our analysis that were affected by fire. In the southern bioregions (yellow) all burned area was included. In the northern bioregions (blue) only rainforest type vegetation was included.

1.4. LIMITATIONS

For each taxon group, we note limitations and caveats specific to those taxa and the methods used to estimate population numbers. Noted in this section are limitations common to all the analyses presented here.

This study highlights the fact that data on population densities are lacking for many taxa in many areas. In addition, some data that were available were decades old (1960s, 1970s, and 1980s), and so may not represent current conditions. Density estimates would have been collected primarily in areas where taxa targeted by individual studies were likely or known to occur, meaning that they may be biased towards higher densities than are typical of those species across their entire geographical ranges. For some taxa, we assumed that each taxonomic group that is present in a bioregion occurs throughout that bioregion at the same average density. This simplifying assumption, while necessary, does not account for variation in densities that would occur seasonally and throughout these large areas, or for the fact that densities of many taxa may have been reduced by the dry conditions that prevailed in eastern Australia in the months before the bushfires.

In addition, this study does not consider fire intensity because mapping of intensity was available only for some areas (e.g., Google Earth Engine Burnt Area Map for NSW, by Department of Planning Industry and Environment 2020), and has not been ground-truthed, and there are limited data with which to link fire severity with impacts on different taxa.

Nonetheless, we consider the estimates of numbers of animals impacted to be conservative, primarily because (1) while each bioregion contains a range of land uses (agriculture, residential, etc.), the burnt areas occurred primarily in areas that were likely to provide good habitat for native vertebrates (e.g., grasslands, woodlands, forested areas); and (2) we consider estimates for impacts only within burnt areas, but animals are likely to have been affected in unburnt areas too, for example, through influxes of animals fleeing burnt areas, heat stress, smoke inhalation, and soil run-off from burnt areas into waterways. As such, while considering the limitations in the data presented here, we expect that the actual number of individual animals impacted by the fires is likely to be higher.

2. MAMMALS

2.1. METHODS

2.1.1. MOST MAMMALS

A literature review was conducted seeking data on population densities of as many native mammal species as possible (excluding marine mammals). The data sources incorporated into the analysis included peer-reviewed literature, government reports, student theses, and personal communications with experts on different taxa. Information extracted from these sources included densities (individuals per hectare), species or species group, and location information. The review resulted in 552 density records, and the data were then categorised into 10 groups, as presented below along with the number of density estimates (*N*) identified by the literature review (Table 2). Where a range of, or several, estimates were provided by a study, a mid-point or average, was included in the analysis (see Appendix 1), although this was uncommon.

We took a different approach to estimate koala densities, as outlined below. There were insufficient data available to generate estimates for some groups, including flying foxes and platypus. Instead, we provide estimates of the proportion of suitable platypus habitat impacted (Appendix 1) and a discussion of the observed impact on some flying fox roosts and foraging ranges.

Limitations on the number of studies that provided ranges or the extent of area over which each estimate was generated, meant that we were only able to generate confidence intervals for our estimates of the number of koalas likely present within the fire impact area.

GROUP	N DENSITY	N SPECIES
ANTECHINUSES, DUNNARTS, AND OTHER INSECTIVOROUS MARSUPIALS	75	24
BATS (MICROCHIROPTERA)	3	3
BETTONGS, BANDICOOTS, QUOKKAS, AND POTOROOS	51	16
DINGOES	15	1
ECHIDNAS	3	1
KANGAROOS AND WALLABIES (INCLUDING ROCK-WALLABIES AND PADEMELONS)	173	28
NATIVE RATS AND MICE	67	17
POSSUMS AND GLIDERS	140	24
QUOLLS AND TASMANIAN DEVILS	14	5
WOMBATS	11	3

Table 2: Number of density estimates (N density) obtained per mammal group and number of species for which densities were obtained (N species).

Using information extracted from the literature review, we mapped the locations where mammal population densities were available. We overlaid these locations onto maps of the Interim Biogeographic Regionalisation for Australia, as noted above, where fires had occurred in our study area and then calculated an average density for each mammal group per bioregion, assuming simply that each group would be distributed uniformly throughout the bioregion. We considered this approach to be particularly valid for the southern regions where forest vegetation types occur over large areas, but acknowledge that it may overestimate densities in the northern region where rainforest occurs in smaller patches.

There were several bioregions for which no data were available, and some bioregions where information was available only for a limited number of taxa (see Appendix A). For each bioregion, we checked species distribution maps in general texts (e.g., Strahan 1995) to identify any species groups that may be present but for which we had no data. For each mammal group that was known to occur in a bioregion, we generated conservative estimates for areas where data were missing by either:

- Using density estimates from a neighbouring bioregion with similar habitats, or
- Applying the lowest actual sampled density estimates from another bioregion (not necessarily neighbouring), or
- Assuming very low densities (e.g., 0.001-0.01 individuals/ha) for groups that occur throughout Australia (e.g., Microchiroptera, echidnas).

2.1.2. KOALAS

We used a combination of methods to estimate the number of koalas impacted by the 2019-20 bushfires. First, we used a study by Adams-Hosking et al. (2016) which drew on expert knowledge to estimate koala population sizes for each bioregion where koalas are known to occur (excluding Kangaroo Island [KI] in South Australia – see below). Adams-Hosking et al. (2016) concluded that there was a mean total koala population of 331,438 (range: 143,958


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– 802,864) in Australia (including KI). We calculated population densities assuming that koalas were uniformly distributed within each bioregion. Adams-Hosking et al. (2016) combined some bioregions in their estimates so we assumed that the populations were evenly distributed across the combined bioregions in order to derive separate estimates per bioregion. We then inferred the number of koalas that would have been impacted by the fires based on the total area burnt within each bioregion. We provide a mean and range of estimates of number of affected individuals based on the bioregional population estimates of Adams-Hosking et al. (2016).

For Kangaroo Island, we used the assessment made by the South Australian Department of Environment and Water (DEW, D. Rogers *pers. comm.* 31/07/2020) which was based on more recent population analyses by Molsher (2017) and Delean and Prowse (2019). The population analyses estimated the koala population on the island to be 48,506 (± 5,976 SE) prior to the fires, with around half occurring in Tasmanian Blue Gum hardwood plantations. DEW estimated that approximately 85% of the population had been impacted by the fires, making a rough estimate that between 5,000 and 10,000 koalas remained after the fires (D. Rogers *pers. comm.* 31/07/2020). For the analysis here, we based our calculations on the assumption that 85% of the Kangaroo Island population was impacted.

A DOWNHILL SLOPE FOR NSW KOALAS

Towards the end of 2019, Biolink Ecological Consultants conducted a review of the conservation status of koalas in NSW (Lane et al. 2020). While the report focused on population declines prior to the fire season, it also included estimates of the proportional decline of koalas in NSW as a result of fires burning between 1 October and 10 December 2019. The report estimated a 19.8% reduction in koala numbers over the preceding three generations prior to the fire events. The authors then made a conservative estimate of 70% mortality in fire-affected areas known to support koalas (Areas of Regional Koala Significance), based partly on on-ground observations that these areas experienced extreme intensity crown fires. This analysis concluded that the fires removed a further 9.46% of the remaining NSW koala population, amounting to approximately 4000 koalas killed by fire in NSW by December 10 2019. The authors therefore recommended listing NSW koalas as Endangered.

Biolink have since resurveyed some of their field sites for koala sign, providing some of the only field-based published data on bushfire impacts to koala populations (Phillips et al. 2020). They found that pre-fire naïve occupancy levels at six sites in NSW fell from 24-71% pre-fire to 0-47% post-fire, with a median reduction in occupancy of 71%.

As noted, we were not able to generate an estimate of the actual number of **platypus** impacted by the fires. Instead, we estimated that 13.6% of available platypus habitat was impacted by fire (Appendix 1, Table 11).

2.2. RESULTS

We estimate that more than **143 million mammals** are likely to have been present within the 2019-20 bushfire impact area (Table 3).

GROUP	NUMBER OF INDIVIDUALS
ANTECHINUSES, DUNNARTS, & OTHER INSECTIVOROUS MARSUPIALS	36,725,000
BATS (MICROCHIROPTERA)	4,976,000
BETTONGS, BANDICOOTS, QUOKKAS, AND POTOROOS	5,573,000
DINGOES	5,000
ECHIDNAS	114,000
KANGAROOS & WALLABIES (INCLUDING ROCK-WALLABIES AND PADEMELONS)	4,963,000
KOALAS *	61,000
NATIVE RATS & MICE	50,406,000
POSSUMS & GLIDERS	38,933,000
QUOLLS & TASMANIAN DEVILS	19,000
WOMBATS	1,184,000
TOTAL	142,899,000

Table 3: Total estimated individual mammals present within the 2019–2020 bushfire impact area. * Note that koalas were calculated using different methodology (see Table 4 below). Estimates per bioregion are provided in Appendix 1.

* For koalas, the mean number of individuals estimated to be impacted was 61,353 (range: 43,261 – 95,180). On Kangaroo Island, if 85% of the population was impacted, this would amount to 41,230 (range: 36,151 – 46,310) individuals, representing 67% of the total estimated impact (Table 4).

STATE	BURNT AREA (HA) IN AFFECTED BIOREGIONS THAT CONTAIN KOALAS	TOTAL POPULATION IN AFFECTED BIOREGIONS THAT CONTAIN KOALAS			INDIVIDUALS AFFECTED		
		MIN	MEAN	MAX	MIN	MEAN	MAX
NSW	5,989,000	17,987	46,816	90,889	3,374	7,817	14,736
QLD	543,000	17,993	45,249	296,108	446	887	9,132
SA (EX. KI)	79,000	10,879	20,719	33,101	23	45	78
SA (KI)	240,000	42,530	48,506	54,482	36,151	41,230	46,310
VIC	1,578,000	39,115	98,536	193,013	3,267	11,374	24,924
TOTAL					43,261	61,353	95,180

Table 4: Estimates of koala populations in bioregions affected by the 2019–20 bushfires (derived from Adams-Hosking et al. 2016 and estimates made by SA Department of Environment and Water) and individuals potentially affected in the bushfire impact area (Environmental Resources Information Network 2020). Calculations were made separately for Kangaroo Island (KI) and the rest of South Australia (SA) (see text). Burnt area is rounded to the nearest 1,000 ha.

GREY-HEADED FLYING FOXES

One group for which there was a paucity of data was bats. In this report, we've calculated estimates for microbats affected by fire based on limited data, mostly collected by the NSW Office of Environment and Heritage. We were not able to obtain density data on flying foxes, but CSIRO researchers have made estimates of the impacts of the 2019–2020 bushfire season on grey-headed flying foxes (Westcott, D. *pers comm.* 8/5/2020). They documented that one grey-headed flying fox camp was burnt and three had some degree of damage, with an estimated 8,650 animals impacted by this damage. Surveys conducted by CSIRO at camps shortly after the fires suggested a significant decline in populations. However, given that flying foxes are highly mobile and camps move regularly (sometimes nightly) it is impossible to know what these impacts mean for flying-fox mortality as the camps may have dispersed. This means that the longer-term consequences of the fires may be more relevant for flying foxes than the immediate impact, via a reduction in foraging area due to loss of suitable habitat. CSIRO estimated that an average of 12% of foraging habitat (native forest) within 20 km of camps (66th percentile of foraging distances) was burnt, extending to 18% of foraging habitat within 40 km of camps (95% percentile). Camps containing 142,000 grey-headed flying foxes (22% of the total population) had at least 20% of their foraging habitat burnt, and 504,000 grey-headed flying foxes (80% of the population) had some foraging habitat burnt. The impacts of the fires on grey-headed flying fox populations may not be realised for another year or more. *Contributed by Dr David Westcott, CSIRO.*

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2.3. CAVEATS

There are several limitations to the methods used to estimate mammal densities. These include:

- Data on population densities extracted from the literature typically represented a single species, but in some cases, it was necessary to average estimates across species groups. Therefore, the estimates do not account for more than one species per group being present in a bioregion. For example, in any given bioregion, if one study found antechinus species X at two individuals/ha and antechinus species Y at four individuals/ha, then densities were averaged across different species of antechinus to produce an estimate of four individuals/ha.
- The estimates we developed where no density data were available are intentionally highly conservative.
- Data are limited for several groups, and as such, estimates of these species have not been included in our total estimate (e.g., platypus, flying foxes).

Additional limitations common to all taxon groups included in this report are outlined in Section 7. Based on these limitations, we consider that the estimate for mammals is likely conservative.

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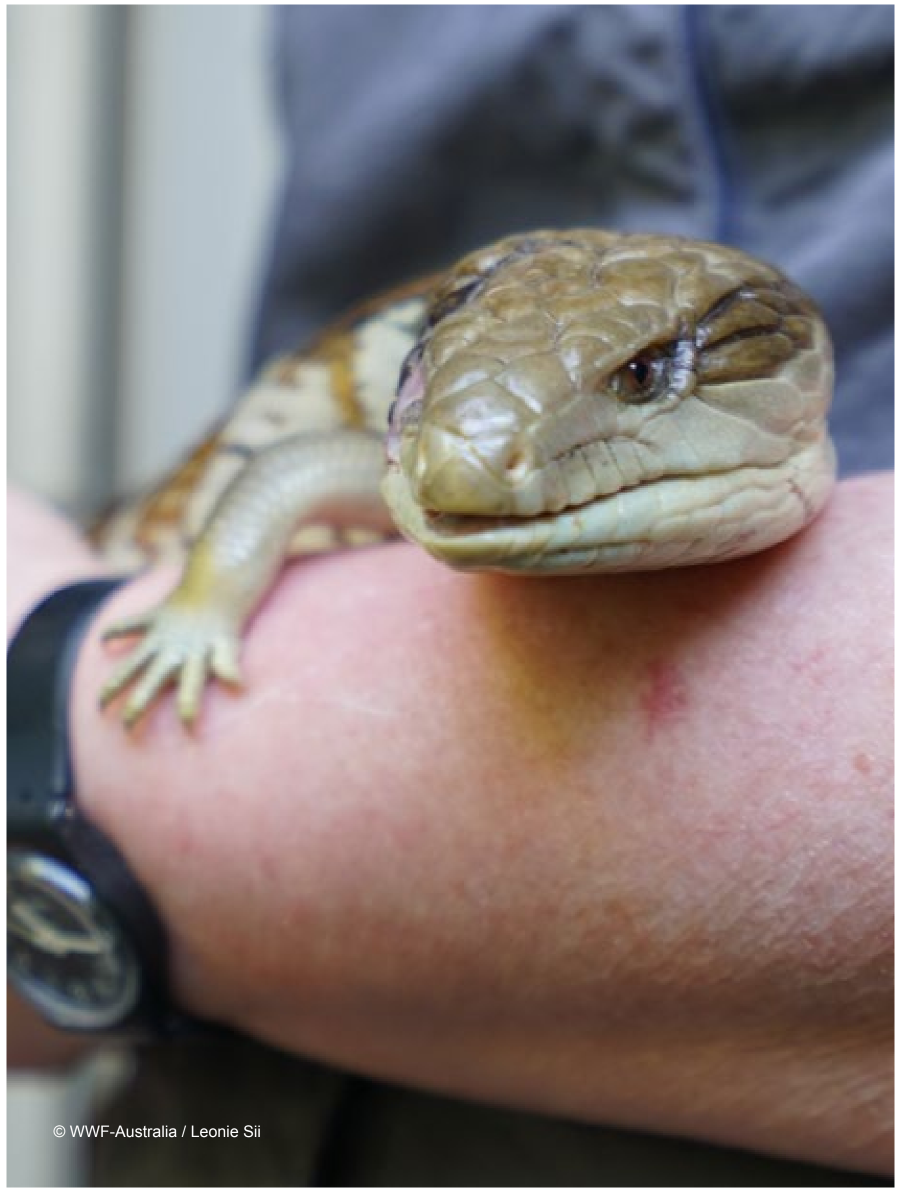
3. REPTILES

3.1. METHODS

We used a modelling approach to derive estimates of the number of individual reptiles in the path of the 2019–20 bushfires. The approach involved several steps.



The first step was to develop a model that could predict the density of reptiles in a given location as a function of broad-scale environmental variables. There are very few density estimates of Australian squamates. Therefore, we drew on a global database of vertebrate density, TetraDENSITY (Santini et al. 2018a), which contained 968 reptile density estimates from locations around the world, including 56 estimates from Australia. Density estimates for reptile species in TetraDENSITY are measured as the number of individuals per hectare. Next, we gathered environmental variables for each location of each density estimate within the TetraDENSITY database. Variables were selected on the basis of previous work showing the importance of Net Primary Productivity (NPP) and precipitation seasonality (Santini et al. 2018b). In addition, we included mean annual temperature and elevation, due to their potential importance in driving reptile density. This final set of environmental variables shared pairwise correlations of <0.7 (Dormann et al. 2013). Body size is also known to affect reptile density (Santini et al. 2018a), with larger species generally occurring at lower densities than smaller species. Therefore, we considered two measures of body size: body length (typically snout-vent length for lizards, total length for snakes) and body mass (derived from family-specific coefficients to convert SVL to mass; Meiri 2010; Feldman & Meiri 2012; Meiri 2018). While body mass has been used previously to model reptile density, we found that body length had a stronger relationship with density, and we therefore used this measure of body size throughout.

We modelled reptile density in relation to the environmental variables and body length using generalised linear mixed models (GLMMs). Mixed models were required to account for the non-independence of density estimates due to there being multiple estimates for some species and relatedness among species in the dataset. To account for this, we included 'species' and 'family' in the model as random effects (following Santini et al. 2018a). We also included a predictor denoting whether or not the density estimate was from Australia, to examine if there were differences in reptile density in Australia compared to other continents, after accounting for environmental variables and body size. Density estimates from Australia did not differ significantly from estimates derived from other continents, and so continent was not considered further during analysis. As density data are continuous and positive (i.e., there are no density estimates below zero), we specified a gamma distribution and a log link function. Models were fitted using the lme package and the glmer function in R version 3.5.3 (Bates et al. 2020). All variables were standardised to ensure that regression coefficients were comparable. We measured model fit using marginal and conditional R-squared (Nakagawa & Schielzeth 2013) using the piecewiseSEM package (Lefcheck 2019). Finally, we measured the predictive capacity of the model by (1) randomly selecting subsets of 50 density estimates from the database, (2) building the model on the remaining data, (3) predicting density for the 50 subsetted density estimates, and (4) comparing the predicted density with the observed density estimates. We repeated this process 20 times and took the Pearson and Spearman rank correlation coefficients to measure congruence between the predicted and observed density estimates.

The second step involved measuring how much of each squamate species' range was affected by the 2019–2020 Australian bushfires. We did this using reptile range maps assembled and vetted by the IUCN working group on Australian squamates (Tingley et al. 2019). The reptile range maps are roughly equivalent to the species' Extent of Occurrence (EOO). While Area of Occupancy data are available for all species, we did not use these for this exercise due to concerns about data quality and bias. After assembling all species' range maps, we intersected the range maps with the fire maps, creating a series of species × fire polygons for each patch that burned a section of a species' habitat. Next, we took the centroid of each of the species × fire polygons in order to extract environmental data for the polygon. We then extracted the same set of environmental variables used in the model developed in step 1.

Next, using the model developed in step 1, we predicted the density per hectare for each species × fire centroid and then multiplied this by the area (in hectares) of each species x fire polygon, to generate an estimate of the number of individuals of each species within each polygon.

Finally, we summed the estimates for all species across all species × fire polygons, deriving a final estimate for the number of species in the path of the 2019–20 bushfires. This required making a decision regarding how much of a species' EOO would be realistically occupied by a given species. Species do not occur across all of their EOO, with holes within their range caused, for instance, by unsuitable habitat and dispersal limitation. Several studies have explored the proportion of appropriate habitat within a species' EOO. The area of suitable habitat within a species' EOO ranges from 23% for 586 birds across the world (Ocampo-Peñuela et al. 2016), 28% for African threatened birds (Beresford et al. 2011), 55% for mammals (Rondinini et al. 2011), to 13% for amphibians (Li et al. 2016). To date, no studies have measured the amount of appropriate habitat within EOO for Australian reptiles. It is important to note that species' actual distributions will not occupy all potentially appropriate habitat, and so the actual distribution of most species will be substantially smaller than the extent of available habitat, due to the occurrence of threats, dispersal limitation, stochastic extinctions, and fine-scale variations in environmental conditions. While potentially unreliable and an under-estimate due to poor sampling of reptiles generally, the Area of Occurrence (measured as the sum of 2 × 2 km grids) for Australian reptiles is on average < 1% of their EOO. On this basis, we decided to assume that, on average, 5% of a species EOO would be occupied at the hectare scale. We used the rbinom function in R to randomly draw samples (in this instance hectares) from each species × fire polygon, setting the probability to 0.05, and used the figures from that random sample as the final multiplier of the density predictions. We calculated the upper and lower 95% confidence intervals of density for each species × fire polygon, and summed these across the same randomly selected hectares to derive confidence intervals for our overall total. We then divided the dataset into two regional datasets to demonstrate spatial variability in the impacts.

3.2. RESULTS

Results from GLMMs showed that all predictor variables had a significant influence on density (Table 5). Body length had the largest effect on density, with larger species having lower densities, as predicted. Precipitation seasonality and elevation also negatively affected reptile density, whereas mean annual temperature and NPP both positively affected density (Table 5). Model fit was high when considering both fixed and random effects (85%), although only a small proportion of this was explained by fixed effects alone (13%), suggesting a strong phylogenetic signal in reptile density. Model validation indicated that there was a moderate to high correlation between predicted and observed densities, depending on the coefficient, with average coefficients of 0.40 (se = 0.016) and 0.67 (se = 0.02) for Pearson's and Spearman rank correlations, respectively.

The median density estimate for individual species at a point (i.e., a species × fire polygon centroid) was 18.96 individuals per hectare (blue dotted line in Figure 3, Appendix 2). Density estimates ranged from 0.05–1769 individuals per hectare, with the lowest densities predicted for large elapids (e.g., *Pseudonaja textilis, Pseudechis porphyriacus*) and the highest densities predicted for small-bodied skinks (e.g., *Cryptoblepharus pulcher, Menetia greyii, and Lampropholis amicula*). Density estimates were highly skewed, with most estimates being close to zero and far fewer large density estimates (Figure 3, Appendix 2). Although estimates of >1,500 individuals of a single species per hectare might seem unrealistic, there are examples of such high densities from Australian ecosystems. For example, Henle (1989) estimated densities of *Morethia boulengeri* of 421–1823 individuals per hectare in inland New South Wales.

Species with the most individuals affected were all lizards, and were generally small (due to the influence of body length in the model) (see Appendix 2), and were mainly species common to eastern and south-eastern Australia. Of the top 20 most affected species, 16 were skinks (family Scincidae), two were geckos (family Diplodactylidae), and 2 were dragon lizards (family Agamidae). The vast majority of animals affected were located in the southern region, where 2.45 billion animals were predicted to be in the path of the fire (CI 775 M–9.57 B; Table 6). A total of 11.43 (CI 4.18 M–47.21 M) million reptiles were predicted to be affected by rainforest fires in the north of Australia. Adding individuals across the two regions, the total number of individuals within the path of the fires is predicted to be **2.46 billion** (CI 779 M–9.62 B). The wide confidence intervals for these predictions reflect considerable uncertainty in the model. The estimate derived from the lower confidence interval here (779 M) could be used as a very conservative estimate of the number of animals in the path of the fire and would equate to an average of 68 reptiles per hectare across the 11.46 million hectares of burned land. However, while this estimate would be statistically conservative, it may not be biologically realistic. We note, for example, that the mean estimate of 2.46 billion aligns closely with numbers that can be derived from density estimates made by experienced field biologists. Thus, Ehmann and Cogger (1985) predicted an average number of 200 individuals per hectare of all reptiles across Australia. If this simple value is multiplied by the area burned in the study area (11.46 million hectares), it yields a total of 2.29 billion reptiles in the path of the fire, close to the model-derived mean estimate of 2.46 billion.

GROUP	COEFFICIENT	STD. ERROR	T VALUE	PR(>|Z|)	
INTERCEPT	2.71	0.50	5.43	0.00	***
LOG (BODY LENGTH)	-1.37	0.29	-4.78	0.00	***
MEAN ANNUAL TEMPERATURE	0.32	0.15	2.06	0.04	*
PRECIPITATION SEASONALITY	-0.65	0.12	-5.59	0.00	***
NET PRIMARY PRODUCTIVITY	0.54	0.07	7.45	0.00	***
ELEVATION	-0.50	0.12	-4.18	0.00	***

Table 5: Parameter estimates from generalised linear mixed models relating reptile density to environmental variables and body length.

REGION	ESTIMATE	LOWER CI	UPPER CI
NORTHERN REGION	11.43	4.18	47.21
SOUTHERN REGION	2,445.94	774.59	9,574.55
TOTAL	2,457.37	778.78	9,621.75

Table 6: Estimates of the number of squamate reptiles (in millions) in the path of the 2019–20 Australian bushfires, including the mean estimate and upper and lower confidence intervals.

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4. BIRDS

4.1. METHODS

BirdLife Australia manages the nationwide 'Birdata' database of volunteer-collected bird survey data. Since 1998 BirdLife has been promoting the use of standardised survey techniques, one of which is the standard 20-minute (min), 2-hectare (ha) area count.

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Surveys are conducted by actively searching a 2-ha area, and recording all birds seen or heard within that area for 20 mins. This time and area standardisation results in broadly comparable estimates of occupancy and/or relative abundance – notwithstanding observer bias and imperfect detection (see Section 4.5 for bias issues).

As is the case for any biological survey method, 20-min 2-ha area surveys are not universally optimal. However, these data constitute an available dataset for estimating bird densities at the (national) scale required for this project.

A total of 232,525 20-min 2-ha surveys were extracted from Birdata (birdata.birdlife.org.au) for the study area. Not all of these surveys contained count data. A total of 100,486 (43% of the total surveys) contained full counts and were used in this analysis. No counts were removed from the dataset (e.g., there were large counts of yellow-faced honeyeaters in migratory flocks or large flocks of woodswallows) as it was considered that these numbers are biologically meaningful – large flocks of birds are likely to be impacted by fires, even if indirectly. Only terrestrial birds (both native and introduced species) were included in the analysis. Marine species and migratory shorebirds are easily defined and are generally accepted within the ecological community. These species are predominately coastal (some migratory species do use inland habitats) and were considered to be minimally impacted by the 2019-20 fires. However, wetland species are more complex. For this report we followed the holistic definition developed by Clemens et al. (2019) that "considered any species that depend on wetlands, waterways or shorelines for feeding or breeding habitats" (Clemens et al. 2019). These species were excluded from the current analysis as, at the time of the exercise, it was unclear the extent to which habitats these species would utilise were directly impacted by the fires. This does not negate the importance of this group of species but reflects the conservative approach taken by BirdLife Australia to consider those species where habitats were known to have been destroyed in the fires.

The final survey dataset was stratified by NVIS groups (using MVG_Name) and IBRA bioregions. Once data had been stratified, mean numbers of birds per 20-min 2-ha survey plus 95% confidence intervals were calculated for each NVIS group and IBRA bioregion combination. These numbers were then used to extrapolate across the extent of the fires to estimate mean bird numbers (and upper and lower ranges). To do this, calculated mean numbers of birds per ha per NVIS group within each bioregion were multiplied by the number of hectares burnt per NVIS group within each bioregion. Confidence intervals were treated in the same way. Final tallies of birds for each NVIS group were summed across each bioregion, giving an overall total of birds potentially impacted during the recent fire events plus an upper and lower estimate. These values are presented in Table 7.

Not all NVIS groups were included in bioregion calculations due to a lack of survey effort across some vegetation types – we don't have data for these vegetation communities and so couldn't come up with estimates. This accounted for about 1% of the burnt area (see Table 7 for bioregion breakdown). To get an overall estimate of birds impacted across the entire fire impacted area, the total of birds calculated for the limited NVIS groups was divided by the total of the used burnt surface area to get an average number of birds per hectare. This value was then multiplied by the total surface area burnt to get an estimate of the total number of birds directly impacted across the whole defined fire area (Table 7).

4.2. RESULTS

The total number of birds estimated to have been impacted by the fires is **180 million** (range: 151,049,499 – 206,798,357). Table 7 provides a summary of the bioregional results, including the number of surveys available for this analysis. Also provided is an indication of the total burnt surface area (ha) for each bioregion [Total area burnt], the total burnt surface area (ha) for the NVIS groups used in this analysis [Used burnt] and the difference in burnt surface area requiring correction to estimate an overall total of birds impacted (either directly or indirectly) as a result of the 2019-20 bushfires.

IBRA BIOREGION	NUMBER OF SURVEYS	ESTIMATE OF INDIVIDUAL BIRDS AFFECTED	UPPER	LOWER	TOTAL AREA BURNT (HA)	USED BURNT (HA)	DIFFERENCE
ARNHEM COAST*	1	10,502	10,502	10,502	5,251	5,251	0
ARNHEM PLATEAU*	9	97,127	151,901	42,352	9,659	9,659	0
AUSTRALIAN ALPS	482	5,325,001	6,209,525	4,440,313	456,670	421,105	35,565
AVON WHEATBELT	1,103	3,645	4,094	3,195	246	246	0
BEN LOMOND	79	137,271	258,033	16,509	27,567	18,516	9,051
BRIGALOW BELT SOUTH	4,545	3,161,583	3,577,774	2,745,391	222,675	222,642	33
CAPE YORK PENINSULA*	134	1,482,349	1,634,731	1,329,967	70,941	70,941	0
CENTRAL ARNHEM*	1	9,660	9,660	9,660	1,288	1,288	0
CENTRAL MACKAY COAST	201	944,573	1,387,852	501,295	32,063	28,629	3,434
COBAR PENEPLAIN	531	8,448	9,602	7,293	464	464	0
COOLGARDIE	3,135	8,886,791	10,005,577	7,768,005	1,011,363	1,010,830	533
DALY BASIN*	2	11,170	18,795	3,544	502	502	0
DARLING RIVERINE PLAINS	806	50,093	70,580	29,606	1,567	1,567	0
DARWIN COASTAL*	34	206,023	258,122	153,923	10,286	10,286	0
EINASLEIGH UPLANDS*	26	128,240	157,069	99,412	6,443	6,443	0
ESPERANCE PLAINS	765	9,83,431	1,235,810	731,052	93,151	92,542	609
EYRE YORKE BLOCK	2,558	211,619	244,412	178,825	24,438	24,406	32
FLINDERS LOFTY BLOCK	6,531	244,636	308,164	180,660	12,873	12,873	0
FURNEAUX	157	13,642	3,832	2,468	3,439	2,809	630
GERALDTON SANDPLAINS	198	11,222	15,602	6,842	815	815	0
JARRAH FOREST	1,282	669,592	786479	552684	63,510	60780	2730
KANMANTOO	1,049	4,036,483	4,720,947	3,352,019	253,755	2,53,451	304
MALLEE	619	2,538,085	2,889,750	2,186,419	310,159	310,102	57
MURRAY DARLING DEPRESSION	5,487	143,322	158,476	128,169	12,610	12,610	0
NANDEWAR	819	1,910,931	2,159,393	1,662,469	88,376	87,597	779
NARACOORTE COASTAL PLAIN	476	691,856	863,101	520,610	40,557	39,047	1,510
NEW ENGLAND TABLELANDS	725	11,439,692	13,098,180	9,781,203	585,655	581,043	4,612
NSW NORTH COAST	3,629	30,424,109	32,458,092	25,761,901	1,961,543	1,959,465	2,078

IBRA BIOREGION	NUMBER OF SURVEYS	ESTIMATE OF INDIVIDUAL BIRDS AFFECTED	UPPER	LOWER	TOTAL AREA BURNT (HA)	USED BURNT (HA)	DIFFERENCE
NSW SOUTH WESTERN SLOPES	6,942	4,580,963	4,854,787	4,307,138	283,163	276,703	6,460
NULLARBOR	333	360,052	490,081	230,022	44,139	40,791	3,348
PINE CREEK*	2	29,713	44,611	14,815	2,764	2,764	0
RIVERINA	6,421	51,489	54,986	47,991	3,152	3,152	0
SOUTH EAST COASTAL PLAIN	6,926	14,855	15,934	13,775	954	954	0
SOUTH EAST CORNER	843	34,249,753	42,386,149	26,113,358	1,924,413	1,907,774	16,639
SOUTH EASTERN HIGHLANDS	9,889	20,271,630	23,835,809	16,707,451	1,351,462	1,337,063	14,399
SOUTH EASTERN QUEENSLAND	4,205	13,412,986	15,968,937	10,857,035	798,632	788,440	10,192
SOUTHERN VOLCANIC PLAIN	2,244	170,558	191,025	150,092	8,401	8,398	3
SWAN COASTAL PLAIN	1,470	575,786	636,242	458,788	26,798	26,791	7
SYDNEY BASIN	12,578	30,302,601	32,729,684	27,873,593	1,652,483	1,643,911	8,572
TASMANIAN NORTHERN SLOPES	138	3,369	4,046	2,693	282	278	4
TASMANIAN SOUTH EAST	1,575	84,953	28,810	22,490	8,115	8,009	106
TASMANIAN SOUTHERN RANGES	235	155	211	98	24	23	1
TASMANIAN WEST	73	6,212	7,976	4,079	3,295	1,336	1959
TIWI COBOURG	20	29,880	42,502	17,259	3,867	3,867	0
VICTORIA BONAPARTE	0	0	0	0	1,710	1,710	0
VICTORIAN MIDLANDS	9,597	157,524	163,105	151,942	10,546	10,521	25
WARREN	831	65,760	103,700	25,555	2,947	2,947	0
WET TROPICS	641	121,012	127,332	114,691	7,022	7,022	0
YALGOO	139	136,139	174,849	97,429	20,570	20,550	20
TOTAL	100,486	178,406,483	204,566,834	149,416,584	11,462,605	11,338,914	123,691

AVERAGE BIRDS PER HA		15.73	18.04	13.18			
FINAL ESTIMATE		180,352,635	206,798,357	151,046,499			

*INDICATES RAINFOREST VEGETATION TYPES ONLY

Table 7: Summary of results for numbers of birds impacted by the 2019–2020 fires for each IBRA bioregion. See text for further description.

4.3. COMPARABLE STUDIES

In the assessment of the impacts of landclearing on fauna made by Johnson et al. (2007), Hugh Ford used numbers of birds/ha that were available in the literature. These referenced studies specifically aimed to quantify the number of birds in the landscape, unlike the BirdLife Australia surveys which are designed to provide a relative abundance value that can be compared at a site over time. The numbers Ford used ranged from a high mean of 35.1 birds/ha in Slopes Open Woodland and Forest to the lowest mean of 1.3 birds/ha in grasslands. Additionally, seasonal effects on bird abundance were not considered in the current analysis.

Woinarski et al. (2017) estimated a mean abundance across all of Australia at 14.2 birds/ha. This number was derived from averaging across a wide range of habitat types, including less productive habitat types that were not included in the current analysis (e.g. arid lands), as well as rainforests, forests, and woodlands. Consequently, we feel that the current estimate of 15.8 birds per ha is plausible, if not conservative (also noting that waterbirds were not included in the current analysis).


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4.4. CAVEATS

The 20-min 2-ha surveys that the data were obtained from are not designed to provide density counts of birds, but rather obtain relative abundance measures for fixed sites. There have been direct studies comparing methods where the differences between relative abundance and absolute abundance have been quantified. There is a general consensus that transects, and area searches underestimate individual bird abundance compared to more intensive methods such as territory mapping or banding studies (see Recher 1988 for review).


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4.5. BIASES IN BIRDATA

Site locations are generally selected by the volunteers collecting the data. This means that placement of sites is not necessarily optimal in terms of getting appropriate spatial coverage or, in this case, appropriate coverage of all NVIS categories. In Appendix 3, we present the spread of surveys across each of the groups across the study area.

It is clear that most surveys were undertaken in areas most accessible to the volunteers collecting the data (Cleared, non-native vegetation, buildings; Eucalypt woodlands and Eucalypt Open forest). Further analysis of the distribution of these NVIS groups and area represented by each is beyond the scope of this study to determine how over-represented certain NVIS groups are in relation to the impact of the bushfires.

Additional biases arising from the Birdata are:

- Peoples' ability to count accurately; risks of double counting individuals (upward), missing birds (downward), over- or underestimating flock sizes.
- The area of 2-ha surveys is not always precisely measured.
- Underestimates of cryptic or nocturnal species. This is a large potential source of downward bias.
- Some bird groups, such as raptors, are known to be under-represented in 20-min 2-ha area searches. Similarly, grassland birds where densities are naturally low are better surveyed using larger-area search methods.
- Low survey effort across certain landscapes. Looking at Table 7, it is obvious that certain IBRAs have low survey effort for the area included in this analysis (e.g., Central Arnhem). Similarly, certain NVIS groups are under-represented in the survey effort (Appendix 3). The degree of underrepresentation is beyond the scope of the current analysis but needs to be acknowledged
- Seasonal effects were not considered in this analysis. Some bird species move to the forests and woodlands of eastern Australia during spring to breed. These increased numbers in spring will have been smoothed out using all seasonal data available in Birdata. This season effect draws attention to the ongoing impacts on Australia's woodland avifauna. Birds will have been faced not only with the immediate impacts of the bushfires during the 2019-20 breeding period but also with ongoing reduction in the quality of breeding habitat that will continue to influence the potential for species population recovery in these areas.

5. FROGS

5.1. METHODS

DEFINITIONS AND ASSUMPTIONS:

This assessment is based on the 67 species of frog that have distributions in eastern NSW and Victoria (study area for frogs) that overlapped with the occurrence of fires.

To estimate the number of frogs impacted by the fires, three steps were taken. The first was to determine the distribution of the frogs, the second was to estimate their density and third to intersect these estimates with the fire footprint to obtain a measure of the number affected by the fires. The first two of these steps required a combination of approaches since the diversity in the life history and habitat use of frogs meant that a single approach was not considered reliable. The methods used are described in Appendix 4, and a brief description is provided below. Assessing the number of frogs directly impacted by the fires (killed) and those indirectly impacted (loss of habitat and foraging), relied on published accounts where pre-and post-fire impacts have been reported and also relied on our expert opinion.

Frogs are not uniformly distributed in the landscape, and it is not valid to map areas and apply density values across a landscape composed of different vegetation communities, watercourses and wetlands. Some frogs spend the majority of their life close to streams or wetlands, while others disperse well away from these sites that they use for breeding, and spend most of their lives in non-stream habitats (usually terrestrial and arboreal micro-habitats). Fire is predicted to impact stream and non-stream habitats differently (Bamford 1992; Driscoll & Roberts 1997; Burrows 2008; Greenberg & Waldrop 2008; Westgate et al. 2012; Potvin et al. 2017; Greenberg et al. 2018). Therefore, to assess the impact of fire on the frog fauna, two approaches were taken.

1) **Frogs that spend most of their lives in-stream habitats were listed.** We used Digital Elevation Model layers to determine the length of stream habitats in the study area and surface hydrology maps for additional wetlands and lakes (Crossman & Li 2015; Geoscience Australia 2015). Using knowledge of the frog species that occur in specific stream habitats, such as those that occur in small mountain streams and those that occur in larger meandering coastal rivers, we constructed a list of frog species for each stream order (Strahler 1957). Information on species occurrence in river catchments was obtained from the Atlas of Living Australia (ALA). We used information from field studies to obtain measures of abundance for each frog species per unit (1 km) of the stream habitats. When combining the density of different species of stream frog together this provided an estimate of the density of frogs per 1 km of stream length. The last step was to overlay the stream layer with that of the footprint of the fire to obtain a measure of the number of frogs within the fire zone.

2) Two approaches were used to determine the **density of frogs that occur in non-stream habitats** (arboreal and terrestrial habitats) since some species have wide distributions with many occurrence records and others have few records and narrow distributions. Firstly, a list of species that occur in non-stream habitats was made. For species that have a large number of records in the ALA, we produced predictive models of distribution using (Maxent, Phillips 2005), applied a measure of abundance per unit area to obtain densities and then overlaid that on the fire footprint. For those species that had few or widely spaced occurrence records in the ALA, and thus where it was not valid to produce predictive distribution maps, we calculated the area of occupancy (AOO) and the alpha-hull distribution. As above, abundance values based on published information and field observations were multiplied by the area occupied to obtain densities which were then overlapped with the fire footprint to obtain an estimate of frog numbers affected by the fire.

Significant habitats occupied by frogs, often in high densities, are coastal wetlands and heaths. Several large fires burnt in coastal swamp ecosystems. These habitats contain large ephemeral wetlands that are only recharged following periods of rainfall and can be dry for prolonged periods of low rainfall and drought. These ecosystems are considered here in the category of non-stream habitats since they are often dry for long periods of the year. We considered using a 'wetland' GIS layer to determine the extent of these habitats but decided that this approach would not effectively represent the extent of habitat use of all the frogs that use these ecosystems. Although several of the species that are specific to these habitats seek shelter in the dense reeds of the wetlands, others—such as the tree frog species—also shelter and forage in the adjacent forests such as paperbark and mahogany swamps, sometimes well away from the wetlands. Using a wetland layer would underestimate the habitat used, and therefore we calculated their diversity and density by the non-stream habitat approach. Distribution maps were developed and abundance estimated for each species. Density of obligate wetland species was calculated by multiplying the area of wetlands with estimates of abundance per hectare.

For all estimates, densities were halved to account for individuals surviving in refuges.

5.2. RESULTS

Sixty-seven species of native frogs are found in the forest and coastal ecosystems of NSW and Victoria. Twenty-three species are listed as threatened under federal and state legislation.

A conservative assessment of the number of frogs impacted by the wildfires in the summer of 2019–2020, in eastern NSW and eastern Victoria, reveals that over **51 million** would have been present within the fire footprint (Table 8). Using the estimated number of frogs in-stream and non-stream (including wetlands) habitats, we calculated the density of 67 frog species within the fire footprint. This included over **23 million pond breeding** and **23 million stream breeding** frogs (Tables 8 and 9). The pattern differed between the tree and ground frogs; with over 20 million tree frog and 2 million ground frogs present along streams (Table 9), while this pattern was partially reversed for pond frogs with over 14 million ground frogs and over 8 million tree frogs assessed to be impacted (Table 9) Similarly, the number of tree frogs and ground frogs impacted in coastal wetlands ecosystems was markedly different (Table 9).

The greatest number of frogs perished in wet forest vegetation communities. Among the tree frogs, over 24 million individuals are assessed to have perished, and over 7 million ground frogs (Table 9).

The total number of individuals of non-threatened species (over 28 million and 22 million for tree and ground frogs, respectively) was greater than for threatened frog species (over 3 million totally; tree frogs over 951,000, over 2 million ground frogs) (Table 9). There are at least two reasons for these outcomes. Threatened species occur in small geographic areas and in low population abundance, and it is therefore not unexpected that the numbers impacted would be lower than for common and widespread species. However, when the impact of fire on threatened species is considered as a cumulative impact on frogs already on the brink of extinction, there is a great risk to the persistence of a number of species. For example, the total number of known locations and AOO for Pugh's forest frog is about 60 km2 ,and over 95% of all known sites were within the fire footprint. Among the tree frogs, 98% of field records for Littlejohn's tree frog south of the Sydney Basin, were within the fire footprint.

	TREE FROGS	GROUND FROGS	TOTAL
NUMBER OF SPECIES	32	35	67
ESTIMATE OF NUMBER OF FROGS AFFECTED (DISTRIBUTION × ABUNDANCE)/2	29,000,000	22,600,000	51,600,000

Table 8: Total numbers of tree frogs and ground frogs likely present within the footprint of the 2019–2020 bushfires. The predicted distribution multiplied by estimated densities of frogs. Density estimates were calculated for each species based on literature and expert opinion. The final total number of frogs estimated to the affected was divided in half to account for the number of frogs that would have survived in micro-refuges.

BREEDING HABITAT. ECOSYSTEM TYPE. THREATENED SPECIES	NO. TREE FROGS	DENSITY: DISTRIBUTION AREA X ABUNDANCE	NO. GROUND FROGS	DENSITY: DISTRIBUTION AREA X ABUNDANCE	TOTALS
BREEDING HABITAT					
STREAM BREEDING	14	20,300,000	10	2,500,000	22,800,000
POND BREEDING	16	8,300,000	13	14,800,000	23,100,000
WETLAND BREEDING	2	352,000	6	5,100,000	5,500,000
OTHER	0	0	6	114,000	
TOTAL	32	29,000,000	35	22,600,000	51,600,000
ECOSYSTEM TYPE					
WET FOREST	10	24,650,000	16	7,800,000	32,470,000
DRY FOREST	1	270,250	12	10,912,675	11,180,000
WOODLAND			1	7,820,000	7,820,000
ALPINE	1	741,000	2	4,900	746,000
COASTAL WETLANDS	5	331,000	3	126,0005	460,000
WIDESPREAD	2	2,960,000	1	3,755,000	6,720,000
TOTAL	32	28,9000,000	35	22,620,000	51,596,000
THREATENED SPECIES	9	951,000	14	2,542,00	3,493,000

Table 9: Numbers of frogs estimated to have been present within the 2019-20 fire footprint, categorised by breeding habitat category, ecosystem type, and threatened species status.

	NUMBER OF FROGS KILLED NSW	NUMBER OF FROGS KILLED VICTORIA	TOTAL NUMBER OF STREAM FROGS KILLED
DENSITY: PREDICTED DISTRIBUTION AREA X ABUNDANCE	20,341,000 TREE FROGS AND 2,546,000 GROUND FROGS (TABLE 8)		22,887,000
LOWER CONFIDENCE LIMITS: STREAM ORDER LENGTH X ABUNDANCE OF FROGS	3,869,000	462,000	4,332,000
MODERATE CONFIDENCE LIMITS: STREAM ORDER LENGTH X ABUNDANCE OF FROGS	15,478,000	1,850,000	17,328,000

Table 10: Comparison of the estimates of number of frogs calculated for predicted distributions and using stream lengths.

Comparison of the two methods for calculating the number of frogs in-stream and non-stream habitats shows that the method of using the length of streams multiplied by the number of frogs per kilometre results in an estimate that is slightly less than that for distribution × density approach (Table 10). We consider that the stream method is more reliable than the predicted distribution × density approach for stream frogs since it is based on the actual length of stream habitats impacted, and the average number of frogs, of several common species, per transect length is reasonably well known.

We have no means to make such a comparison for pond and swamp breeding species since we do not have a spatial layer for the occurrence and size of these habitats, and we must rely on the predicted distribution method. Furthermore, there are several forest species (e.g., Litoria chloris, Litoria dentata, Assa darlingtoni and Lechriodus fletcheri) that do not use permanent ponds and whose breeding locations are distributed across their mapped forest habitats. The only way to deal with the density of these species, in a manner that can the replicated, is to use the predicted distribution approach.

Greater than 90% of the 67 frog species are found only in natural forested habitats, with only a few species occurring in human-dominated landscapes (cleared agricultural land and urban landscapes), and our estimates are restricted to naturally vegetated areas.

5.3. CAVEATS

Not all frog species have the same abundance in the landscape. Densities based on published field studies were used to estimate the number of frogs per unit area for species where that information was available (Appendix 4). However, there are few empirical studies that provide information on density for many species, and therefore we used expert opinion to estimate densities. In some cases, this involved using values from studies on closely related species with similar ecologies. There were, however, numerous species for which this was not possible, and in these cases, we used indicators of abundance of presence records in the Atlas of Living Australia and expert opinion.

Another assumption is that the density of frogs is uniform within the mapped predictive distribution for a species or along the length of streams. For the assessment of density in predictive distributions and along streams we relied on abundance reported in empirical studies and on our own field experience for several species. Frogs do not use all components of the ecosystem equally, and therefore density measures based on habitat categories rely on certain assumptions. Most obviously, frogs congregate around ponds or streams to breed, and there is evidence that these habitats with higher moisture content in the landscape are subject to different intensity burns than other habitats such as ridges and mid-slopes. However, many frog species move considerable distances away from the breeding site into surrounding habitats to forage and seek shelter. They may be at the breeding site for only a few days in the summer season (e.g., green-thighed frog, Litoria brevipalmata, males call at the breeding pond for two to three days a season), and others live there for several months (e.g., Peron's tree frog, Litoria peronii). In forest ecosystems, ponds vary in occurrence, some forests have many and others have few. Since these are the habitats used by pond breeding species, the number and distribution of ponds will affect the total density of frogs in a forest. At another scale, many coastal wetlands and swamps can be relatively large, covering several square kilometres after rainfall, and the density of frogs can be very high. For these reasons, the method adopted was to calculate density values for each of the 67 species of frog independently using published accounts and expert knowledge on the abundance of each, rather than combining all frog species on a community basis and calculating a density for different ecosystems or regions.

The taxonomy and nomenclature used are those used by the Atlas of Living Australia (Fauna of Australia). However, there are several species and species complexes where the correct identification of taxa and their record-locations in the ALA database have not been updated to accommodate current taxonomic revisions. Importantly, the lack of correct species identity should not affect the mapping of fire impact, since the records represent a true presence of one of these species, and there is no double counting of records in the approach used.

The mapping of distributions for each of the frogs does not include consideration of distributions where species have disappeared (e.g., large areas of known habitat formerly occupied by Litoria raniformis on the southern tablelands and south-western slopes in NSW, and large areas formerly occupied by Litoria booroolongensis in northern NSW). In these cases, the extent of habitat destroyed may be extensive, but individuals of these species would not have been killed by the fires, since they no longer are found there. However, these are areas where recolonization by the frogs may have occurred, and re-introduction efforts now may be more difficult due to the fire. Furthermore, if we are incorrect and there were small and isolated remnants of some species that have declined from other threats in the past, the extent and severity of the fires would only serve to exacerbate that decline and isolation.

6. DISCUSSION

In total, we estimate that almost **3 billion** native vertebrates are likely to have been present within the 2019-20 bushfire areas. Our estimate comprises approximately:

- 143 million mammals
- 2.46 billion reptiles
- 181 million birds
- 51 million frogs

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These are estimates of the numbers of individuals within selected taxon groups that were likely to have been present within the impact area of the 2019-20 bushfires. We will never know the true number of individuals killed by the fire, although future efforts to quantify this could be informed by our study in combination with research on other factors such as the ability of different taxa to survive fire.

6.1. THE DATA DEFICIT

There are many limitations in the data that prevent us from developing a more accurate estimate of the impacts of bushfires, especially during atypical intense and extensive fire seasons such as what occurred over 2019-20. These include data on densities of different taxa, an understanding of different species' abilities to survive and their responses to different fire regimes and burn intensities, and the interactions of fire with other landscape stressors in impacting individual and population survival (Driscoll et al. 2010). This is the case for both common and threatened species.

Long-term ecological monitoring provides an ideal opportunity for both identifying the short-term impacts of, and recovery from, bushfires on ecosystems and monitoring the long-term changes caused by climate change. For example, some of the areas burned in 2019-20 have been experiencing changed fire regimes, particularly an increase in fire frequency which may reduce the ability of some species to recover (Lindenmayer & Taylor 2020) To maximise the effectiveness of such monitoring, it should be carried out broadly, and ideally, we believe, in all bioregions.

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6.2. INDIRECT AND COMPOUNDING THREATS

There are immediate, direct impacts of bushfires on animals (e.g., being burnt in the fire or suffocating from smoke inhalation). The species composition of local and regional biotas will likely change, with some species (e.g., successional species or generalists that can exploit varied resources) benefiting while others lose out. These longer-term threats could result in the extinction of species that are not well adapted to frequent burning, adding to Australia's already-high extinction rate. Many such at-risk species have been identified by the Expert Panel established by the Australian government in the wake of the 2019-2020 bushfires, but others undoubtedly remain. For example, at least 20 species of slug and land snail were in the path of fires that ravaged Mount Kaputar in NSW in late 2019; with the exception of the iconic giant pink slug (*Triboniophorus aff. graeffei*), it is not clear how the other species have fared (https://www.abc.net.au/news/2020-01-29/giant-pink-slug-mount-kaputar-national-park-survived-bushfire/11911308). Similar fears are held about the fate of other species, such as the Kangaroo Island micro-trapdoor spider and Kangaroo Island assassin spider (*Zephyrarchaea austini*) (*Moggridgea rainbowi*) (Marsh 2020; Rix 2020).

Alongside mortality caused by direct exposure to flames, smoke inhalation, heat, and sediment run-off, fire interacts with other stressors, exacerbating threats to the persistence of threatened species and ecosystems. Three of the greatest threats to Australian flora, fauna, and ecosystems are altered fire regimes, invasive species, and landclearing; all threats interact with and compound one another (Doherty et al. 2015). The approximately 3 billion vertebrates that we estimate to have been present within the burnt area is in addition to more than 2 billion frogs, lizards, birds, and mammals estimated to be killed annually by feral and domestic cats in Australia (Woinarski et al. 2017; Woinarski et al. 2018; Murphy et al. 2019; Woinarski et al. 2020b) and more again by red foxes (Saunders et al. 2010). These estimates of predation are derived for populations in the absence of a major fire event and many populations can potentially recover because of this. However, post-fire, habitats may not be suitable for many species for years or decades, so recovery - and stochastic population risks - will be long term problems. For example, it took almost 20 years for greater gliders Petauroides volans to be detected in Royal National Park following major fires (Andrew et al. 2014). Burned landscapes can cause decreased availability of resources, increased competition with conspecifics, and increased predation risk (e.g., from cats and red foxes) due to lack of protective vegetative cover and shelter (McGregor et al. 2014; Doherty et al. 2015).

Combined with loss of habitat caused by clearing, fragmented habitat and cleared land can provide favourable habitat for invasive species, reducing the ability of some native species to recover from fire. Some species may be able to flee fire, seeking shelter and migrating to new habitat. However, landclearing decreases habitat availability and connectivity, thus reducing availability of refuges, and has altered fire regimes in Australia (Johnson et al. 2007).

6.3. AUSTRALIA'S NATIONAL AND INTERNATIONAL OBLIGATIONS

Among the objectives of the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*—Australia's major legislative instrument for nature conservation—are the imperatives to conserve Australian biodiversity and to provide for the protection of the environment, especially matters of national environmental significance (MNES). MNES include species and ecological communities that are listed as threatened, migratory species, world heritage properties and national heritage places. Legislative instruments designed to protect biodiversity and environmental values are in place also in every state and territory in Australia, often mirroring the provisions of the EPBC Act. As this report describes, the dramatically negative effects of the 2019-20 bushfires have very likely contravened the objectives of existing legislation, and provide a strong imperative to mitigate the risks arising from such events in future.

At the international level, Australia is the custodian of World Heritage Sites on behalf of all humanity. As a signatory to the UNESCO World Heritage Convention, the nation accepts the responsibility to manage these places for their outstanding universal values which, for the two such sites—the Greater Blue Mountains and the Gondwana Rainforests of Australia—are natural values around biodiversity. The 2019-20 bushfires burnt some 81% of the Greater Blue Mountains and 54% of the Gondwana Rainforests, thus again impacting negatively on the outstanding natural values of these places and potentially compromising our national commitment to protect them. In addition to committing to protecting areas with outstanding universal values, Australia is also a signatory to the Convention on Biological Diversity (CBD). Aichi Target 12 of the CBD, established for the period 2011–20, states that "By 2020, the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained." Yet the most recent report by Australia to the CBD, in 2014, noted that "Recent State of the Environment reports and previous national reports, including those submitted to the CBD, have expressed moderate to high levels of concern about the decline in many groups of fauna in Australia" (Australian Government 2014: 10). The 2019-20 bushfires are again, as described in this report, likely to have exacerbated declines in many threatened species and groups of threatened fauna, suggesting that Australian actions to help meet commitments to the CBD must be reviewed and strengthened.

In the section below, we provide a number of recommendations to improve monitoring and management of future bushfires and their impacts on biodiversity. We hope that the approaches suggested meet societal expectations, as well as national and international obligations.

6.4. FUTURE CONSIDERATIONS

The direct impacts of the fires and additional compounding stressors have killed large numbers of individual animals as well as potentially amplified the speed of decline of threatened species and ecosystems and placed at risk further species and ecosystems that were not previously considered threatened. Climate change predictions suggest that fires will intensify and expand and fire seasons will extend (Lewis et al. 2019; van Oldenborgh et al. 2020), so it is critical that we consider how to mitigate these impacts in future years. Several blueprints for future action have already been proposed (e.g., DAWE 2020; Dickman et al. 2020; Lindenmayer & Taylor 2020), and commissions of inquiry and review are underway at the state and national levels. Here, we propose some key recommendations to improve monitoring, recovery, and the management of future bushfires and their impacts that pertain especially to the vertebrate fauna.

To better understand the impacts of bushfires:

- Implement appropriate long-term monitoring research in all bioregions that are likely to be at risk in future bushfires.
- Identify and map the distributions of biota that are likely to be most at risk in future bushfires, such as those with restricted ranges and those not well-adapted to fire.
- Identify communities and key populations of fire-susceptible species, and areas where populations of such species co-occur, and develop strategies to reduce the risk of high-intensity fires in these areas including protecting these during fires.
- Identify key resources and management actions (e.g., food, water, shelter, protection from introduced predators or competitors) that are required by wildlife, especially fire-susceptible species, to maintain their populations and persist in the wake of a bushfire.
- Experimentally evaluate the effectiveness of different post-fire methods to manage and ensure the persistence of species and communities that are not well-adapted to fire.
- Develop standard national methodologies for surveying and modelling animal densities across all taxon groups (which may differ for different taxa).

To mitigate bushfire impacts on biota and appropriately manage risk:

- Improve habitat connectivity (i.e., by protecting existing vegetation and revegetating elsewhere) to ensure access to fire refuges for mobile species during and following fire.
- Identify and protect unburnt habitat that is critical habitat for threatened species recovery and build fire recovery actions into species Recovery Plans and Conservation Advices under the EPBC Act (Fitzsimons 2020).
- Establish improved fire prevention and management practices, drawing from traditional ecological knowledge where possible and appropriate to do so.
- Reduce further impacts on biota that can occur in the post-fire environment such as elevated predation, clearing, salvage logging, removal of logs, dead wood and other structures that provide shelter to fire-survivors.
- Establish rapid response teams that will act to assess and mitigate impacts on threatened species and ecosystems when fires occur, using both in situ and ex situ (e.g., wildlife rescue) approaches, as appropriate. As proposed by the Threatened Species Recovery Hub (Dickman et al. 2020) actions may include:
    - » Prioritising locations that harbour important biota for bushfire prevention and control;
    - » Protecting key refuge areas;
    - » Rescuing injured wildlife and providing water and food, both in situ and ex situ;
    - » Conducting rapid assessments of biodiversity loss shortly after the event;
    - » Identifying and mitigating compounding threats (e.g., landclearing, invasive species, sediment run-off).

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APPENDICES

APPENDIX 1 - MAMMALS

BIOREGION	ANTECHINUS, DUNNARTS & OTHER INSECTIVOROUS MARSUPIALS	BATS (MICRO)	BETTONGS, BANDICOOTS, QUOKKAS, & POTOROOS	DINGOES	ECHIDNAS	KANGAROOS & WALLABIES	NATIVE RATS & MICE	POSSUMS & GLIDERS	QUOLLS & DEVIL	WOMBATS	IMPACT AREA (HA)
ARNHEM COAST		0.100	0.300	0.001	0.010	0.017	0.670	0.100			5,240
ARNHEM PLATEAU		0.100		0.001	0.010	0.017	0.670	0.320			9,732
AUSTRALIAN ALPS	5.625	0.100		0.002	0.010	0.010	19.500	12.260	0.010	0.167	456,773
AVON WHEATBELT	1.290	0.100		0.001	0.015	0.096		0.430			246
BEN LOMOND		0.100			0.010	0.460	0.100	0.291	0.050	0.100	27,567
BRIGALOW BELT SOUTH	0.010	0.100		0.002	0.010	0.429		0.912			222,652
CAPE YORK PENINSULA	3.060	0.100		0.001	0.010	0.007	1.610	0.100			71,281
CENTRAL ARNHEM		0.100		0.001	0.010	0.017	0.670	0.100			1,307
CENTRAL MACKAY COAST		0.100		0.002	0.010	0.060		0.100			31,893
COBAR PENEPLAIN	0.010	0.100		0.000	0.010	0.200		0.100			465
COOLGARDIE	0.080	0.100		0.001	0.010	0.027		0.100	0.000		1,011,198
DALY BASIN		0.100		0.001	0.010	0.107	0.670	0.100			508
DARLING RIVERINE PLAINS	0.010	0.100		0.000	0.010	0.125		0.100			1,567
DARWIN COASTAL		0.100		0.001	0.010	0.020	0.670	1.747	0.115		10,328
EINASLEIGH UPLANDS	0.193	0.100	0.275	0.002	0.010	0.411	1.908	0.734	0.006		6,468
ESPERANCE PLAINS	0.100	0.100		0.001	0.010	0.096		173.000			93,365
EYRE YORKE BLOCK		0.100		0.000	0.010	1.500		0.100			24,436
FLINDERS LOFTY BLOCK		0.100		0.000	0.010	0.067		0.100			12,860
FURNEAUX		0.100			0.010	0.911	0.100	1.261	0.037	0.100	3,431
GERALDTON SANDPLAINS	0.515	0.100		0.001	0.010		3.880	0.100			815
KANMANTOO		0.100			0.010		11.000	0.100			253,723
MALLEE	0.010	0.100		0.001	0.010	0.096		0.100	0.004		310,278
MURRAY DARLING DEPRESSION		0.100		0.000	0.010	0.081	2.100	0.100		0.210	12,606
NANDEWAR	0.010	0.100		0.000	0.010	0.200		0.100			88,293
NARACOORTE COASTAL PLAIN		0.100			0.010		12.500	0.100			40,555
NEW ENGLAND TABLELANDS	2.440	0.030		0.002	0.010	0.742		0.100		0.100	585,429
NSW NORTH COAST	3.660	1.200	2.450	0.000	0.010	1.700	1.806	0.597	0.003	0.200	1,961,797
NSW SOUTH WESTERN SLOPES	10.750	0.100		0.000	0.010	0.348		0.100		0.167	282,996
NULLARBOR	0.080	0.100		0.000	0.010	0.027		0.100			44,178
PINE CREEK	1.330	0.100	0.500	0.001	0.010	0.107	0.670	0.336			2,761
RIVERINA		0.100		0.000	0.010	0.270		1.038			3,154
SOUTH EAST COASTAL PLAIN	0.053	0.100	0.435	0.000	0.010	1.875		4.333		0.100	961
SOUTH EAST CORNER	5.365	0.100		0.000	0.010			0.115	0.001	0.100	1,924,881
SOUTH EASTERN HIGHLANDS	5.365	0.100	0.300	0.000	0.010	0.361	19.265	7.108	0.001	0.167	1,350,808
SOUTH EASTERN QUEENSLAND	5.633	0.100	0.230	0.001	0.010	0.390	10.332	0.912			798,625
SOUTHERN VOLCANIC PLAIN	7.676	0.100	2.025		0.010	1.388	3.916	1.865			8,391
SWAN COASTAL PLAIN	0.010	0.100	4.444	0.001	0.010	0.560	0.100	5.877			26,827
SYDNEY BASIN	0.010	1.140		0.000	0.010			2.850		0.100	1,652,680
TASMANIAN CENTRAL HIGHLANDS		0.100			0.010	0.335	0.100	0.299	0.007	0.100	282
TASMANIAN NORTHERN MIDLANDS		0.100			0.010	0.350	0.100	0.100	0.050	0.100	8,115
TASMANIAN SOUTH EAST		0.100			0.010	0.273	0.100	0.216	0.050	0.600	24
TASMANIAN SOUTHERN RANGES		0.100	0.190		0.010	0.164	12.350	1.606	0.190	0.100	3,295
TIWI COBOURG		0.100	0.460	0.001	0.010	0.020	12.750	0.892			3,846
VICTORIA BONAPARTE		0.100		0.001	0.010	0.107	0.670	0.100			1,736
VICTORIAN MIDLANDS	2.700	0.100			0.010	0.158	6.000	1.953		1.900	10,535
WARREN	0.010	0.100	7.5	0.001	0.010	0.875		3.200			2,956
WET TROPICS		0.100	0.656	0.001	0.010	0.060	1.610	0.861			7,052
YALGOO		0.100	0.352	0.001	0.010	0.635	0.100	0.100			20,523
TOTAL											11,462,954

Table 11: Estimated densities of populations of mammal groups (individuals per hectare) per bioregion and total burnt area per bioregion (ha).

BIOREGION	ANTECHINUS, DUNNARTS, & OTHER INSECTIVOROUS MARSUPIALS	BATS (MICRO)	BETTONGS, BANDICOOTS, QUOKKAS, & POTOROOS	DINGOES	ECHIDNAS	KANGAROOS & WALLABIES	NATIVE RATS & MICE	POSSUMS & GLIDERS	QUOLLS & DEVILS	WOMBATS	TOTAL ANIMALS
ARNHEM COAST	0	524	1,572	3	52	90	3511	524	0	0	6,276
ARNHEM PLATEAU	0	973	0	5	97	167	6520	3114	0	0	10,876
AUSTRALIAN ALPS	25,69348	45,677	0	822	4,568	4,568	8,907,074	5,600,037	4,568	76,129	17,212,791
AVON WHEATBELT	317	25	0	0	4	23	0	106	0	0	475
BEN LOMOND	0	2,757	0	0	276	12,681	2757	8,022	1,378	2,757	30,628
BRIGALOW BELT SOUTH	2227	22,265	0	362	2,227	95,462	0	202,984	0	0	325,527
CAPE YORK PENINSULA	21,8120	7,128	0	36	713	502	11,4762	7,128	0	0	348,389
CENTRAL ARNHEM	0	131	0	1	13	22	876	131	0	0	1,174
CENTRAL MACKAY COAST	0	3,189	0	68	319	1,914	0	3,189	0	0	8,679
COBAR PENEPLAIN	5	47	0	0	5	93	0	47	0	0	197
COOLGARDIE	80,896	101,120	0	1,011	10,112	27,050	0	101,120	394	0	321,703
DALY BASIN	0	51	0	0	5	54	340	51	0	0	501
DARLING RIVERINE PLAINS	16	157	0	0	16	196	0	157	0	0	542
DARWIN COASTAL	0	1,033	0	5	103	209	6,920	18,040	1,188	0	27,498
EINASLEIGH UPLANDS	1,245	647	1779	14	65	2,661	12,341	4,745	41	0	23,538
ESPERANCE PLAINS	9,337	9,337	0	93	934	8,916	0	16,152,145	0	0	16,180,762
EYRE YORKE BLOCK	0	2,444	0	2	244	36,654	0	2,444	0	0	41,788
FLINDERS LOFTY BLOCK	0	1,286	0	1	129	862	0	1,286	0	0	3,564
FURNEAUX	0	343	0	0	34	3,127	343	4,326	126	343	8,642
GERALDTON SANDPLAINS	420	82	0	1	8	0	3,162	82	0	0	3,755
KANMANTOO	0	25,372	0	0	2,537	0	2,790,953	25,372	0	0	2,844,234
MALLEE	3103	31,028	0	310	3,103	29,632	0	31,028	1,210	0	99,414
MURRAY DARLING DEPRESSION	0	1,261	0	1	126	1025	26,473	1261	0	2647	32794
NANDEWAR	883	8,829	0	9	883	17,659	0	8,829	0	0	37,092
NARACOORTE COASTAL PLAIN	0	4,056	0	0	406	0	506,938	4,056	0	0	515,456
NEW ENGLAND TABLELANDS	1428447	17563	0	1171	5854	434461	0	58543	0	58543	2004582
NSW NORTH COAST	7180177	2354156	4806403	196	19618	3335055	3543496	1170539	5885	392359	22807884
NSW SOUTH WESTERN SLOPES	3042207	28300	0	28	2830	98341	0	28300	0	47166	3247172
NULLARBOR	3534	4418	0	4	442	1182	0	4418	0	0	13998
PINE CREEK	3672	276	1381	1	28	296	1850	928	0	0	8432
RIVERINA	0	315	0	0	32	852	0	3272	0	0	4471
SOUTH EAST COASTAL PLAIN	51	96	418	0	10	1802	0	4164	0	96	6637
SOUTH EAST CORNER	10326184	192488	0	192	19249	0	0	221361	1925	192488	10953887
SOUTH EASTERN HIGHLANDS	7246522	135081	405242	135	13508	488092	26022797	9602144	1351	225135	44140007
SOUTH EASTERN QUEENSLAND	4498921	79863	183684	719	7986	311464	8251127	728080	0	0	14061844
SOUTHERN VOLCANIC PLAIN	64409	839	16992	0	84	11643	32859	15649	0	0	142475
SWAN COASTAL PLAIN	268	2683	199219	27	268	15023	2683	157653	0	0	377824
SYDNEY BASIN	16527	1884055	0	165	16527	0	0	4710138	0	165268	6792680
TASMANIAN CENTRAL HIGHLANDS	0	28	0	0	3	94	28	84	2	28	267
TASMANIAN NORTHERN MIDLANDS	0	812	0	0	81	2840	812	812	406	812	6575
TASMANIAN SOUTH EAST	0	2	0	0	0	7	2	5	1	14	31
TASMANIAN SOUTHERN RANGES	0	330	626	0	33	539	40693	5293	626	330	48470
TIWI COBOURG	0	385	1769	2	38	78	49037	3430	0	0	54739
VICTORIA BONAPARTE	0	174	0	1	17	186	1163	174	0	0	1715
VICTORIAN MIDLANDS	28445	1054	0	0	105	1665	63210	20570	0	20017	135066
WARREN	30	296	22170	3	30	2587	0	9459	0	0	34575
WET TROPICS	0	705	4624	4	71	423	11354	6069	0	0	23250
YALGOO	0	2052	7216	21	205	13032	2052	2052	0	0	26630
TOTALS	36,725,309	4,975,728	5,573,094	5,414	113,996	4,963,227	50,406,131	38,933,358	19,101	1,184,131	142,899,489

Table 12: Estimated number of individual mammals within the bushfire impact area per group per bioregion.

ESTIMATES FOR IMPACTS ON PLATYPUS

Data on platypus occurrence and population density are lacking. Instead, we made an assessment of the proportion of platypus habitat burnt based on modelling that has been used to estimate platypus extinction risk prior to the 2019-20 bushfire season (Bino et al. 2020).

The methods are a variation of those used in Bino et al. (2020). We collated 11,830 platypus observations (1760–2017) from the national Atlas of Living Australia (www.ala.org.au) and atlas records held by individual states and territories (ACT Wildlife Atlas Records 2018; BioNet Atlas of NSW Wildlife 2018; Tasmania Natural Values Atlas 2018; Victorian Biodiversity Atlas 2018; WildNet Queensland Wildlife Data 2018), using these as the most systematic compilation of observations available. We also included another 184 historical records from digitized newspaper records (Hawke et al. 2019). We removed records with missing years of sightings and duplicates (matching coordinates and year of sighting).

To model habitat suitability of platypus, we used the Biodiversity & Climate Change Virtual Lab and the Maximum Entropy Species Distribution Modelling approach (Phillips & Dudik 2008). To increase model accuracy, we excluded platypus records from the overall Atlas databases (n = 11,830) with a spatial accuracy less precise than 10 km (n = 1,992), leaving us with 9,838 occurrence records (1760–2017), which we spatially aligned to the nearest stream (Stein et al. 2014). We then randomly generated an equal number of background pseudo-absences (Barbet-Massin et al. 2012). We considered 11 explanatory variables, biologically relevant to platypus and based on the stream and nested catchment framework for Australia (Stein et al. 2014). These included four environmental variables of contemporary climate (annual mean temperature, maximum temperature of warmest month, annual precipitation, precipitation of driest quarter; 1921-1995 (Xu & Hutchinson 2013)), two terrain variables (stream order and maximum segment elevation) (Hutchinson et al. 2008), two current woodland and forest cover variables (Australian Government 2006a, b), percentage of urban and modified land (not for conservation) within the catchment area and the river disturbance index (Stein et al. 2014).

Our rationale for including temperature was based on the species' thermal tolerance (W Robinson 1954) and for precipitation on the dependence of platypus on freshwater habitats (Bino et al. 2019). We included terrain variables, given the species' habitat preference for mid and lower river reaches (Serena et al. 1998; Turnbull 1998; Rohweder & Baverstock 1999; Serena et al. 2001; Koch et al. 2006; Olsson Herrin 2009; MacGregor et al. 2015). We also incorporated tree cover, as riparian trees provide shelter, burrows and organic matter for prey, while cleared areas increase erosion and sedimentation of rivers (Rohweder 1992; Bryant 1993; Serena et al. 2001; Milione & Harding 2009; Ellem et al. 19989). Predictive performance of the platypus distribution model was evaluated using the area under the receiver operating characteristic curve (AUC) and Cohen's Kappa using a ten-fold cross-validation analysis (Stockwell 1992; Fielding & Bell 1997; Hijmans 2012).

To estimate the extent to which platypus were exposed to bushfires, we used the predicted probability of occurrence derived from the developed habitat suitability model. Following examination of model accuracy, we removed probabilities lower than P = 0.25. We then summed probabilities (cell size 250 m × 250 m) across all Australian bioregions that intersected with the predicted platypus distribution. Within each bioregion, we then calculated the sum of probabilities that overlapped with the extent of the recent bushfires (Environmental Resources Information Network 2020) and calculated their proportion from the sum of probabilities across the entire bioregion.

We estimated that 13.6% of available platypus habitat was impacted by fire (Table 13)

individual bird abundance compared to more intensive methods such as territory mapping or banding studies (see Recher 1988 for review).

BIOREGION	CODE	PROPORTION OF PLATYPUS HABITAT BURNED
AUSTRALIAN ALPS	AUA	28%
BEN LOMOND	BEL	2%
FURNEAUX	FUR	<1%
NANDEWAR	NAN	3%
NARACOORTE COASTAL PLAIN	NCP	1%
NEW ENGLAND TABLELANDS	NET	13%
NSW NORTH COAST	NNC	30%
NSW SOUTH WESTERN SLOPES	NSS	6%
RIVERINA	RIV	<1%
SOUTH EAST COASTAL PLAIN	SCP	<1%
SOUTH EAST CORNER	SEC	62%
SOUTH EASTERN HIGHLANDS	SEH	11%
SOUTH EASTERN QUEENSLAND	SEQ	8%
SOUTHERN VOLCANIC PLAIN	SVP	<1%
SYDNEY BASIN	SYB	24%
TASMANIAN NORTHERN SLOPES	TNS	<1%
TASMANIAN SOUTH EAST	TSE	<1%
TASMANIAN WEST	TWE	<1%
VICTORIAN MIDLANDS	VIM	<1%
WET TROPICS	WET	<1%

Table 13: Impacts of the 2019-20 bushfire season on modelled platypus habitat (proportion of sum of probabilities of platypus occurrence) based on (Bino et al. 2020).

APPENDIX 2 - REPTILES

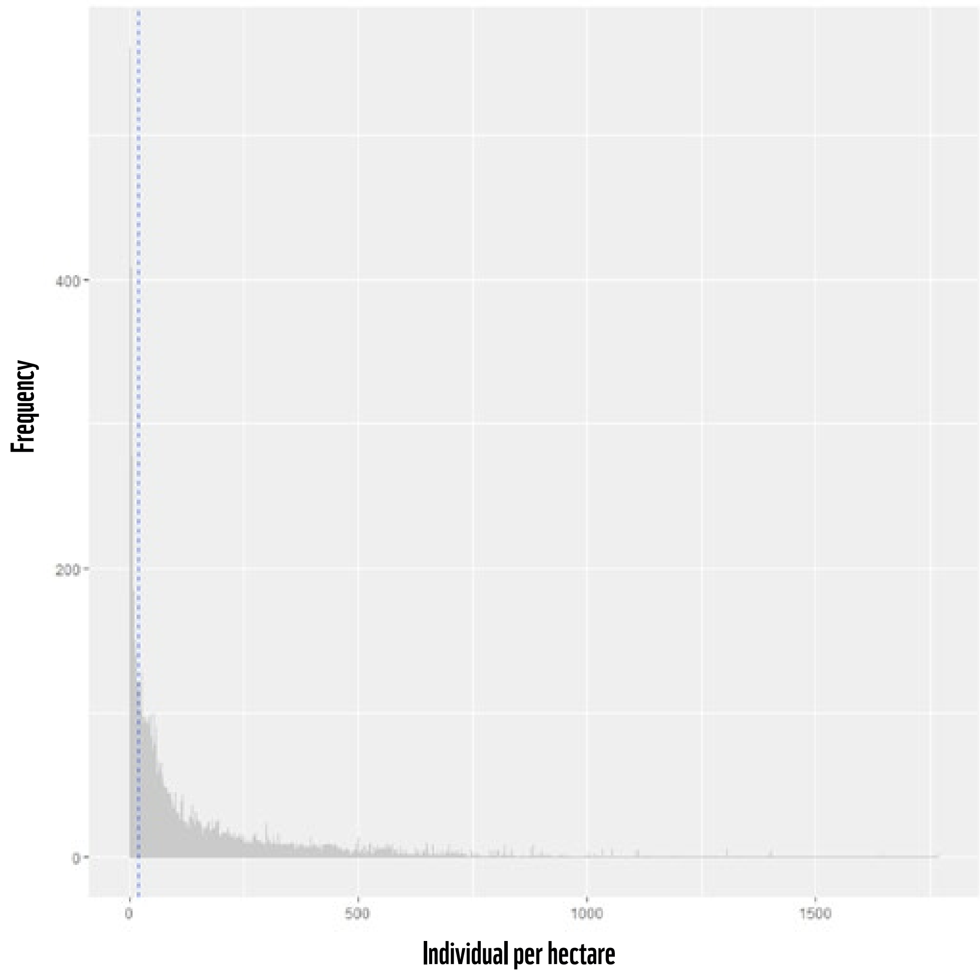

Figure 3: Histogram of density estimates (individuals per hectare) for squamate reptiles across the fire affected study area. Blue dotted line = the median number of individuals/ha across all estimates (18.96 individuals per hectare).

SPECIES	SUB ORDER	FAMILY	LENGTH (MM)	INDIVIDUALS
CRYPTOBLEPHARUS PULCHER	SAURIA	SCINCIDAE	42	643,380,264
LYGISAURUS FOLIORUM	SAURIA	SCINCIDAE	43	460,041,973
LAMPROPHOLIS GUICHENOTI	SAURIA	SCINCIDAE	52	420,007,672
LAMPROPHOLIS DELICATA	SAURIA	SCINCIDAE	55	412,339,692
LAMPROPHOLIS AMICULA	SAURIA	SCINCIDAE	35	364,900,447
CARLIA VIVAX	SAURIA	SCINCIDAE	50	225,541,171
MORETHIA BOULENGERI	SAURIA	SCINCIDAE	57	192,283,978
SAPROSCINCUS MUSTELINUS	SAURIA	SCINCIDAE	64	164,929,283
PSEUDEMOIA ENTRECASTEAUXII	SAURIA	SCINCIDAE	65	158,069,367
MENETIA GREYII	SAURIA	SCINCIDAE	40	150,043,740
CONCINNIA TENUIS	SAURIA	SCINCIDAE	85	149,709,374
CTENOTUS SPALDINGI	SAURIA	SCINCIDAE	105	135,687,322
DIPORIPHORA NOBBI	SAURIA	AGAMIDAE	84	132,123,943
RANKINIA DIEMENSIS	SAURIA	AGAMIDAE	84	124,618,012
ANEPISCHETOSIA MACCOYI	SAURIA	SCINCIDAE	59	118,020,241
HEMIERGIS TALBINGOENSIS	SAURIA	SCINCIDAE	60	114,476,610
CTENOTUS TAENIOLATUS	SAURIA	SCINCIDAE	89	111,520,405
DIPLODACTYLUS VITTATUS	SAURIA	DIPLODACTYLIDAE	60	108,752,268
PSEUDEMOIA SPENCERI	SAURIA	SCINCIDAE	65	92,508,666
NEBULIFERA ROBUSTA	SAURIA	DIPLODACTYLIDAE	85	88,024,234

Table 14: The 20 squamate reptile species with the largest predicted populations in the path of the 2019–2020 Australian bushfires. Individuals = number of individuals estimated to be within the fire-affected areas.

APPENDIX 3 - BIRDS

NVIS GROUP (MVG_NAME)	NUMBER OF SURVEYS	PER CENT OF SURVEYS	BURNT SURFACE AREA (HA)	PER CENT AREA BURNT
CLEARED, NON-NATIVE VEGETATION, BUILDINGS	44,375	39.17	1,071,847	4.99
EUCALYPT WOODLANDS	22,642	19.99	7,607,475	35.40
EUCALYPT OPEN FORESTS	11,148	9.84	4,869,569	22.66
NA	6,376	5.63		0.00
MALLEE WOODLANDS AND SHRUBLANDS	6,352	5.61	416,754	1.94
INLAND AQUATIC - FRESHWATER, SALT LAKES, LAGOONS	2,066	1.82	35,729	0.17
REGROWTH, MODIFIED NATIVE VEGETATION	1,905	1.68	6795	0.03
RAINFORESTS AND VINE THICKETS	1,797	1.59	372,661	1.73
CHENOPOD SHRUBLANDS, SAMPHIRE SHRUBLANDS AND FORBLANDS	1,731	1.53	32,391	0.15
OTHER SHRUBLANDS	1,586	1.40	18,1315	0.84
MELALEUCA FORESTS AND WOODLANDS	1,547	1.37	527,985	2.46
EUCALYPT OPEN WOODLANDS	1,265	1.12	1,014,676	4.72
UNKNOWN/NO DATA	1,218	1.08	26,982	0.13
OTHER GRASSLANDS, HERBLANDS, SEDGELANDS AND RUSHLANDS	994	0.88	464,243	2.16
HEATHLANDS	993	0.88	220,592	1.03
CASUARINA FORESTS AND WOODLANDS	844	0.75	20,076	0.09
LOW CLOSED FORESTS AND TALL CLOSED SHRUBLANDS	704	0.62	22,120	0.10
TROPICAL EUCALYPT WOODLANDS/GRASSLANDS	667	0.59	1,899,916	8.84
ACACIA SHRUBLANDS	623	0.55	7,1317	0.33
EUCALYPT TALL OPEN FORESTS	609	0.54	1,146,854	5.34
TUSSOCK GRASSLANDS	597	0.53	112,471	0.52
OTHER OPEN WOODLANDS	535	0.47	613,305	2.85
OTHER FORESTS AND WOODLANDS	410	0.36	185,640	0.86
ACACIA FORESTS AND WOODLANDS	403	0.36	131,464	0.61
MANGROVES	362	0.32	38,021	0.18
CALLITRIS FORESTS AND WOODLANDS	322	0.28	32,393	0.15
NATURALLY BARE - SAND, ROCK, CLAYPAN, MUDFLAT	320	0.28	30,162	0.14
MALLEE OPEN WOODLANDS AND SPARSE MALLEE SHRUBLANDS	202	0.18	49,665	0.23
ACACIA OPEN WOODLANDS	189	0.17	539	0.00
UNCLASSIFIED NATIVE VEGETATION	180	0.16	2,158	0.01
HUMMOCK GRASSLANDS	138	0.12	87,083	0.41
EUCALYPT LOW OPEN FORESTS	109	0.10	17,4514	0.81
SEA AND ESTUARIES	60	0.05	5,678	0.03
UNCLASSIFIED FOREST	12	0.01	18,175	0.08

Table 15: NVIS grouping, number of 20-min, 2-ha surveys and the % of overall survey effort used in this analysis. Also presented is the total burnt surface area and the per cent of the total burnt surface area.

APPENDIX 4 - FROGS

This section contains definitions and data used to inform the methods and results for amphibians.

Rationale for the approach adopted: There are published works that have used empirical field observations of frog counts per habitat area in Australia (Bamford 1992; Driscoll & Roberts 1997; Westgate et al. 2012), but most of these studies have reported on one or at most a few species, and the range of ecosystems and habitat covered is limited. Densities of frogs caught in replicated trapping studies have found unexpectedly high numbers in some habitats (Morton et al. 1993; Westgate et al. 2012; Ocock 2013; Read 19991), however these studies in arid habitats have usually involved only one or two species (but see Westgate et al. 2012; Ocock 2013). Density counts of frogs along stream habitats, around ponds and in larger wetlands have been made by numerous studies (Gillespie & Hollis 1996; Osborne & McElhinney 1996; Morrison et al. 2004; Heard et al. 2006; Lane et al. 2007; Lane & Burgin 2008; Stratford et al. 2010; Heard et al. 2012), but once again most studies focus on one or two species, with a preponderance of studies focused on distribution with respect to habitat features; few address the matter of abundance or density. There are some exceptions, but these are usually for species of conservation concern (e.g., corroboree frog, Eungella day frog, Booroolong frog, alpine tree frog, and Spencer's tree frog). Such species are likely to be rarer in the environment or concentrated in small patches and a fire in an area of concentration could be disastrous for the species. Large landscape fires will affect many individuals of species that are more widespread and common.

When mapped in a cumulative fashion, with each species' distribution added as a layer in GIS, the pattern is complex, and it was decided that it was not possible to use a single estimated frog density for the study area. Similarly, it was not possible to come to density measures for major vegetation community types. This approach would require fewer assumptions than a single density value, but the differences in vegetation communities do not show a close correspondence with the distribution of frog species across the range of vegetation communities. However, for certain vegetation communities, such as cool temperate rainforest, or wallum heath, this approach was considered to be potentially valuable.

To address the matter of density of frogs per area, the approach taken was to calculate numbers of frog of a species in its core distribution. Core distribution is defined as the >90% predicted occurrence in a geographic area (300 x 300 m pixel) based on a fundamental niche model.

Fundamental niche models were developed using the program MAXENT (Phillips 2005) and followed developed procedures. Primary information used in model construction was presence records held in the Atlas of Living Australia. Following an expert process to remove spurious records, the models were constructed following standard procedures (Elith & Leathwick 2009; Keith et al. 2014; Penman et al. 2015). Distributions were manually clipped to an approximate 100 km boundary around the minimum convex polygon of record distribution, and a training level of 20% removal of records was chosen (Elith et al. 2011). The MAXENT model was constructed using only climate layers, and a common set of variables was used (see appendix). While this approach fails to consider some specific climate attributes the may be correlated with the distribution of some frog species, it was assumed that the climate variables associated with frog species across eastern Australia were similar. To have optimised variable combinations for each of the species would have been very time consuming.

Once the predicted geographic distribution (>90% predicted occurrence in 300 × 300 m pixels) for a species were obtained these were intersected with the map of fire occurrence, to obtain the total area that was impacted by fire for that species. This step was repeated for species guilds.

Methods to calculate density of frogs:

1. We placed the 67 species of frog known to occur on the Great Dividing Range and eastern slopes in NSW and Victoria into the two habitat categories of "stream" and "non-stream". Wetland species were placed in the non-stream category for the purpose of the analysis.

These species of frog were divided into the two broad habitat categories, steam and non-stream.

Stream frogs are defined as species that spend greater than 90% of their life within the stream zone (commonly called the riparian zone, i.e., about 50 m from the mid-line of the stream).

Non-stream habitat frogs are defined as species that spend greater than 90% of their life away from the stream zone. This group includes some frogs that visit the stream to breed, and their tadpoles live in the stream (and there are fire impacts on stream habitats that affect them); however, the majority of time is spent away from the stream zone, and the potential impact of fire is assessed in the non-stream component of the habitat.

There are two reasons for choosing to subdivide the frog fauna on habitat basis to determine the density of frogs in the landscape and the potential impact of the fires; the first is the expected difference in fire impact on stream versus non-stream habitats, and the second is methodological. It is important to recognise that stream and non-stream habitats would be impacted by fires in different ways because near stream habitats have concentrations of moisture compared to non-stream habitats (Crossman & Li 2015; Geoscience Australia 2015). The methodological reason is the availability of a geographic information system layer (GIS layer) for the geographic position, length and order (Strahler 1957), of all mapped streams. This means that by having information on the community composition of frog species using streams, and their density, it is possible to estimate the total number of frogs in-stream habitats.

To address the question of the density of frogs in non-stream habitats, we chose to predict the distribution by modelling the fundamental niche of the more common species using standard methods. Occurrence records for each individual species were obtained from the Atlas of Living Australia (ALA), and the fundamental niche mapped to predict the distribution. Occupancy that was predicted with a >70% confidence was chosen. Estimates of the density of frogs within the mapped distribution were determined for each species based on field studies, and expert opinion. For many species of frog there is limited information on abundance, and our estimates of density are based comparative studies (Tyler 1998; Gillespie & Hines 1999; Hines et al. 1999; Parris & McCarthy 1999; Parris 2004; Mahony et al. 2013). For those species where the ALA had few or widely spaced records and a robust predictive distribution model was not possible we calculated the area of occupancy (AOO) and the alpha-hull value to obtain the area distribution. Total numbers were obtained by estimating the number of frogs per hectare.

2. Estimates of the number of frogs in these two habitat categories used different approaches.

2.1. Density of frogs in-stream habitats (defined as the riparian zone extends approximately 50 m either side of the stream mid-line):

Using the Atlas of Living Australia (ALA), we developed maps of the distribution of the frogs in the stream habitat category, by constructing polygons for the extent of occupancy (EEO). Using expert knowledge, we determined the major river catchments in which the species occurred from the EEO so that we could map the catchments in which they occur.

To calculate the density of frogs along streams, we used a Geographic Information System (GIS) layer of the streams in eastern New South Wales and Victoria. Streams were subdivided into first, second and third-order classes (Strahler 1957), and the GIS layer used to determine the total lengths within the distribution of a species. Relying on published and expert information on the number of individuals of a species along a typical stream we calculated the density per unit length (1 km of stream)

This is a useful approach for frogs since most species are adapted to one or perhaps two-stream orders, and thus the diversity and number of frogs along a stream can be readily determined (Gillespie 1990; Gillespie & Hollis 1996; Gillespie & Hines 1999; Hines et al. 1999; Lemckert & Morse 1999; Parris & McCarthy 1999; Parris et al. 1999; Lemckert & Brassil 2000; Hazell et al. 2001; Lemckert & Slatyer 2002; Parris 2002; Hazell et al. 2003; Lemckert & Brassil 2003; Parris 2004; Penman et al. 2006; Penman et al. 2007; Penman et al. 2008; Lemckert & Mahony 2010; Lemckert 2011; Gillespie et al. 2016; Scheele & Gillespie 2018).

Furthermore, the number of frogs per length of stream order can be estimated (with upper and lower confidence limits) so that a density per unit length (e.g., 1 km) can be calculated.

A frog density score per kilometre, for each stream order, was calculated based on studies that have measured community composition and abundance (see above). This value was multiplied by the total length of that stream order to obtain a total population estimate.

To calculate the number of frogs affected by fire, we aligned the fire intensity map with the stream layer. The total number of frogs impacted was obtained by multiplying the density score with length of streams impacted.

2.2 Density of frogs found in non-stream habitats (this is defined as habitat greater than 50 m from the riparian zone):

Three steps were involved; 1) As above we assigned frog species to this habitat category, 2) the distribution area for each frog species was determined using a modelling approach (see Appendix), 3) the estimate of the density of a frog species per unit of distribution area were based on published field studies, 4) we calculated the intersection of the species distribution with the mapped fire distribution, and 5) the population density was multiplied by the area of the fire impact to obtain an estimate the number of frogs affected by the fire.

This approach was not suitable for all non-stream frogs because in some cases the number of occurrence records in the Atlas of Living Australia was too small to enable a robust predicted model of distribution and the EEO would produce an overestimation of the real distribution. In these cases, we calculated the area of occupancy (AAO) using a 2 × 2 km pixel for each record to obtain an estimate of the distribution. It is likely that this approach underestimates the extent of distribution, and therefore the extent of impact on these species. The low number of records is most likely an indication of rarity, and it is expected that the numbers impacted would therefore be low and not have a large effect on the estimate of the frogs impacted. However, it is also the case that these species are threatened and the fire many have been catastrophic to small and isolated populations. We do not address these cases in this report.

Method to assess the number of frogs affected directly and indirectly:

Because of the differences in adaptations of frogs and the habitats they use it is likely that not all species will be affected in the same way by fire. There is information for a small number of species that demonstrate these differences (Driscoll & Roberts 1997; Penman et al. 2006; Westgate et al. 2012). Burrowing frogs may have some protection depending on the depth that individuals have burrowed (Penman et al. 2006), and small pond breeding tree frogs may survive in moist riparian areas (Lemckert & Brassil 2000; Potvin et al. 2017). Several studies estimating post-fire abundance using abundance measures from counts and call surveys have indicated that frog species are resilient to fire (Bamford 1992; Ford et al. 1999; Engbrecht & Lannoo 2012; Westgate et al. 2012). However, there is evidence that counts of animals may not provide a clear indication of the effect of fire on frog populations. In a study that included pre-and post-fire abundance measures accompanied by population genetic information, there was not a significant difference between the counts, but there was a significant difference in the effect population size and indication of loss of genetic diversity (Potvin et al. 2017). Unfortunately, there is insufficient information for the majority of species to enable an assessment of the effect of fire on individual species, and we have taken a conservative approach. After calculating the density of frogs in the fire impacted habitats, we divide the outcome by half. We are aware that this introduces a level of uncertainty in the assessment of impact, but consider that this presents a conservative and realistic assessment.

Impact of fire on tadpoles not assessed: The aquatic "tadpole" life stage of the frogs are not considered in this assessment of impact. We have chosen not to consider the impact on these animals for several reasons. We are not aware of any studies that have examined the effect of fire on tadpoles in streams or ponds, and we have no direct evidence on which to postulate how fire affects them. Secondly, we have no estimates of the number of tadpoles in streams based on empirical studies, although we recognise that it would be a large number. Thirdly, we have no information on how the fire would directly or indirectly affect these animals. It is likely that tadpoles would not be directly affected by fire as long as they are in sufficiently large bodies of water. However, studies on other aquatic organisms indicate that water pollution is a significant component of post-fire environmental habitat alteration and we, therefore, assume that tadpoles would potential be indirectly affected in this way (Adams & Simmons 1999; Minshall 2003; Bixby et al. 2015). Because of these uncertainties, any calculation of the numbers impacted, that we could make, would be based on assumptions for which we have no empirical information.

Definitions Used:

IUCN Red List. (http://jr.iucnredlist.org/documents/redlist_cats_crit_en.pdf)

Area of Occupancy (AOO). The IUCN recommendation for the grid size used to calculate AOO is 2 km. This grid is placed over all selected taxon records within the user-defined area.

"Area of occupancy [AOO] is defined as the area within its 'extent of occurrence' which is occupied by a taxon, excluding cases of vagrancy. The measure reflects the fact that a taxon will not usually occur throughout the area of its extent of occurrence, which may contain unsuitable or unoccupied habitats. In some cases (e.g. irreplaceable colonial nesting sites, crucial feeding sites for migratory taxa) the area of occupancy is the smallest area essential at any stage to the survival of existing populations of a taxon. The size of the area of occupancy will be a function of the scale at which it is measured…"

Extent of Occupancy (EOO). Using the ALA, EOO is calculated as the minimum convex hull based on the "presence" taxon occurrence records within the user-defined area.

"Extent of occurrence [EOO] is defined as the area contained within the shortest continuous imaginary boundary which can be drawn to encompass all the known, inferred or projected sites of present occurrence of a taxon, excluding cases of vagrancy (Figure 2 IUCN 2012). This measure may exclude discontinuities or disjunctions within the overall distributions of taxa (e.g. large areas of obviously unsuitable habitat). Extent of occurrence can often be measured by a minimum convex polygon (the smallest polygon in which no internal angle exceeds 180 degrees and which contains all the sites of occurrence)."

Alpha Hull for EOO

"The alpha hull value is used when calculating the Extent of Occupancy (EOO) for assessing conservation risk. It examines the distance between occurrence points and modifies the area to be included in the EOO based on a multiple (alpha - selected by the user) of the average distance between points. The lower the alpha value, the tighter the EOO will be around the occurrence points" (https://www.iucnredlist.org/documents/RedListGuidelines.pdf)

"The bias associated with estimates based on convex hulls (EOO), and their sensitivity to sampling effort, makes them less suitable as a method for comparing two or more temporal estimates of EOO for assessing reductions or continuing declines. If outliers are detected at one time and not another, this could result in erroneous inferences about reductions or increases. Therefore, a method such as the α-hull (a generalization of a convex hull) is recommended for assessing reductions of continuing declines in EOO because it substantially reduces the biases that may result from the spatial arrangement of habitat (Burgman and Fox 2003). The α-hull provides a more repeatable description of the external shape of a species' range by breaking it into several discrete patches when it spans uninhabited regions. For α-hulls, the estimate of area and trend in area also converges on the correct value as sample size increases, unless other errors are large. This does not necessarily hold for convex hulls. Kernel estimators may be used for the same purpose, but their application is more complex." (ALA 2019).

"To estimate an α-hull, the first step is to make a Delauney triangulation of the mapped points of occurrence. The triangulation is created by drawing lines joining the points, constrained so that no lines intersect between points. The outer surface of the Delauney triangulation is identical to the convex hull.

STREAM ORDER (STRAHLER CLASSIFICATION)	METRES	STATE	NO OF KM	AVERAGE FROGS/KM	TOTAL FROGS	TOTAL FROGS KILLED
1	24,363,664	NSW	24,363	100	2,436,366	
2	11,443,126	NSW	11,443	100	1,144,312	
3	5,777,070	NSW	5,777	50	288,853	
NSW TOTAL					3,869,532	3,869,532
1	2,959,741	VIC	2,959	100	295,974	
2	1,359,385	VIC	1,359	100	135,938	
3	611,823	VIC	611	50	30,591	
VICTORIA TOTAL					462,503	462,503
TOTAL						4,332,036

Table 16: Number of frogs estimated per kilometre by Stream Order in NSW and Victorian catchments mapped against the fire footprint.

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