Threatened Species Recovery Hub

National **Environmental Science** Programme

Estimating wildlife mortality during the 2019–20 bushfire season

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*Cover image: Yellow-footed Antechinus (*Antechinus flavipes*). Image: Patrick Kavanagh CC BY 2.0*

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Executive summary

The 2019–20 Australian megafires drew the close attention of global audiences to the plight of animals exposed to these unprecedented fires. Yet, we know remarkably little about the direct impacts of fire on animal mortality, stymieing our ability to predict the impacts of these fires on native wildlife populations. In January 2020, Professor Chris Dickman predicted that >1 billion animals had been affected by the 2019–20 megafires. Yet those predictions were admittedly 'back of the envelope', based on animal density estimates previously used to predict the mortality of birds, reptiles, and mammals due to land clearing. In this study, we aimed to drastically improve our capacity to predict the numerical impact of fires on native Australian wildlife. To achieve this, we needed to improve our understanding of how many animals would be predicted to die in a fire of a given magnitude, as well as improve density estimate models to predict the number of animals expected in a given parcel of land. In theory, these aims could then be combined to predict the numerical outcomes of a given fire on animal mortality. First, we conducted a global systematic review on the direct impacts of fire on wildlife. We determined that fire severity had a significant effect on animal mortality, with severe fires killing more animals than mild fires (on average 2% vs. 7%). Additionally, overall direct mortality caused by fire was relatively low (e.g., on average only 3% of animals were killed in any given fire). We also developed a framework for estimating the number of animals within the boundary of the 2019–20 megafire by combining a global database of animal densities and fire maps. Together, these two pieces of research bring us closer to being able to predict the immediate impacts of megafires on wildlife more reliably; but, as we discuss, several challenges remain. Because there are so few studies of the direct effects of fire on animal mortality, we still lack sufficient resolution on the impacts of fire on animal mortality to make generalised predictions on the numbers of animals likely killed as a direct result of fires of varying magnitudes. Our data suggest only a relatively small proportion (3% [1–9%]) of animals are likely to die as a direct result of fire, although further studies of animal survival during severe fire and megafires are badly needed. Potentially, population declines following fire may be driven primarily by the challenges faced in the post-fire environment (e.g., elevated predation, and limited food, water, and shelter). This, however, presents an opportunity for conservation practitioners to focus attention on addressing these impacts following major wildfire events.

*Red-backed Fairy-wren (*Malurus melanocephalus*). Image: David Cook Wildlife Photography, CC BY-NC 2.0*

Introduction

In January 2020, Professor Chris Dickman's prediction that >1 billion animals had been affected by the 2019–20 megafires focused the world's attention on the severity of impacts upon Australia's wildlife. Yet those predictions were admittedly 'back of the envelope', based on animal density estimates previously used to predict the mortality of birds, reptiles, and mammals due to land clearing in NSW (Johnson *et al.* 2007). However, mortality estimates from land clearing—where it is reasonable to assume most animals living in an area die when the area is cleared—are not directly applicable to predictions of mortality in wildfires. This is because at least some animals can and do survive fires. Whether an animal dies during fire depends on behavioural, physiological, and morphological traits of the animal, characteristics of the environment (e.g., fuel loads), and the behaviour of the fire (e.g., intensity, rate of spread). The most useful and reliable empirical data on how many animals die during fire come from studies that track individuals before and after a fire event, allowing a calculation of the proportion of the study animals that lived and died. Yet these data are scattered throughout an increasingly voluminous and dispersed scientific literature, and prior to this project, there had been no synthesis of studies documenting fire-induced mortality.

In this project, we reviewed the global data on fire-induced wildlife mortality in an attempt to develop a greater understanding of the number of terrestrial vertebrates (amphibians, birds, mammals, and reptiles) killed during fires, to help contextualise the impacts of the 2019–20 megafires on wildlife. We also developed a framework for estimating the number of animals within the boundary of the 2019–20 megafire by combining a global database of animal densities and fire maps. Together, these two pieces of research bring us closer to being able to predict the immediate impacts of megafires on wildlife more reliably; but, as we discuss, several challenges remain.

Main aims of the research

Our project consisted of three aims that intended to improve our ability to estimate the effects of fire on the mortality of wildlife, with particular interest in estimating wildlife mortality during the 2019–20 bushfires. Our project aims were to:

1. Undertake a global systematic review and meta-analysis of fire-induced mortality in wildlife
2. Develop a modelling framework for estimating densities of species' populations in fire-prone ecosystems
3. If possible, use findings from Aims 1 and 2 to develop more robust estimates of wildlife mortality during fires, and apply this approach to enumerate mortality during the 2019–20 fires, and to allow for such estimates in future fires.

Methodology

The project intended to improve our ability to estimate the direct effects of fire on the mortality of vertebrate wildlife. Note that our assessment focuses on vertebrate wildlife only, but we use 'wildlife' and 'animals' generally as simple and interchangeable terms.

The first stage of the project (Aim 1) was to improve understanding of the direct impacts of fire on animal mortality (i.e., how many animals die during fire?). To achieve this, postdoctoral research fellow Chris Jolly led a global systematic review of all studies investigating the direct impacts of fire on animal mortality. Note that this assessment included studies considering a wide range of fire intensities, and many of the studied fires would have been of far lower intensities than the Australian wildfires of 2019–20. To be certain that we were assessing the direct effects only of fire on mortality, we required studies that tracked multiple animals through the passage of fire and then assessed the proportion of animals that survived. Most of these studies were 'tracking' studies, where researchers used animal tracking technologies to find animals after a fire has passed and determined their fate. Other approaches to the assessment of mortality in fires (such as studies that compared density estimates at monitored sites pre- and post-fire, or studies that examined persistence of marked, but not tracked, animals at sites pre- and post-fire) were considered for this review, but we excluded these because they could have confounded mortality in fire with post-fire dispersal away from fire.

Our systematic and supplementary (i.e., non-structured Google Scholar searches) searches returned 2,919 studies, of which 31 met our inclusion criteria. These studies provided 43 instances of the direct effects of fire on mortality of 31 species. From these 31 studies, we extracted data on various attributes of the study species, the study environment, and the fire (Table 1). We used these data to visualise the spread of studies through time and space, and assessed them for temporal or regional biases. After excluding studies that tracked few individuals ($n < 5$), we used generalised linear mixed models with binomial errors and logit link to assess how mortality differed according to fire type (planned vs wildfire), fire severity (mild vs severe), body mass (log-transformed continuous variable), ecology (terrestrial, arboreal vs volant), and animal class (amphibian, bird, mammal vs reptile).

The second aim of our project (Aim 2) was to develop a framework for estimating species' population densities in fire-prone ecosystems. Associate Professor Dale Nimmo led this part of the project. This work was undertaken in collaboration with the World Wide Fund for Nature, which published a report on the number of animals in the path of the 2019–20 bushfires (van Eeden *et al.* 2020). A large database was used, that catalogued animal density estimates from around the world TETRADensity (Santini *et al.* 2018), to develop a modelling framework for predicting the number of animals in the path of the fire. As a case study, density estimates of reptiles from around the world were modelled against environmental variables such as net primary productivity, mean annual temperature, and elevation. As the body size of animals affects their density (small animals tend to occur at higher densities than larger animals), this trait was also included as a predictor variable in the models. Predictions were then made of the number of animals within the boundaries of the 2019–20 megafires, based on the environmental conditions and traits of species within the fire-grounds, using reptiles as a case study.

The final aim of the project (Aim 3) was to use the findings from Aims 1 and 2 to enumerate animal mortality during the 2019–20 Australian megafires (Fig. 1). We identified that fire-induced mortality was not well understood, and that there may be too few estimates to generalise about fire-induced mortality. Such a finding would suggest a vital long-term research need to track animal mortality during fire to fill this gap. Given the limited data available detailing fire-inducted mortality gathered from the systematic review (Aim 1), and the considerable gaps in the data (outlined below), we were not comfortable deriving an estimate of the number of animals that died during the 2019–20 fires on the basis of available information on fire-induced mortality. Nonetheless, our findings do have management implications in a broader sense.

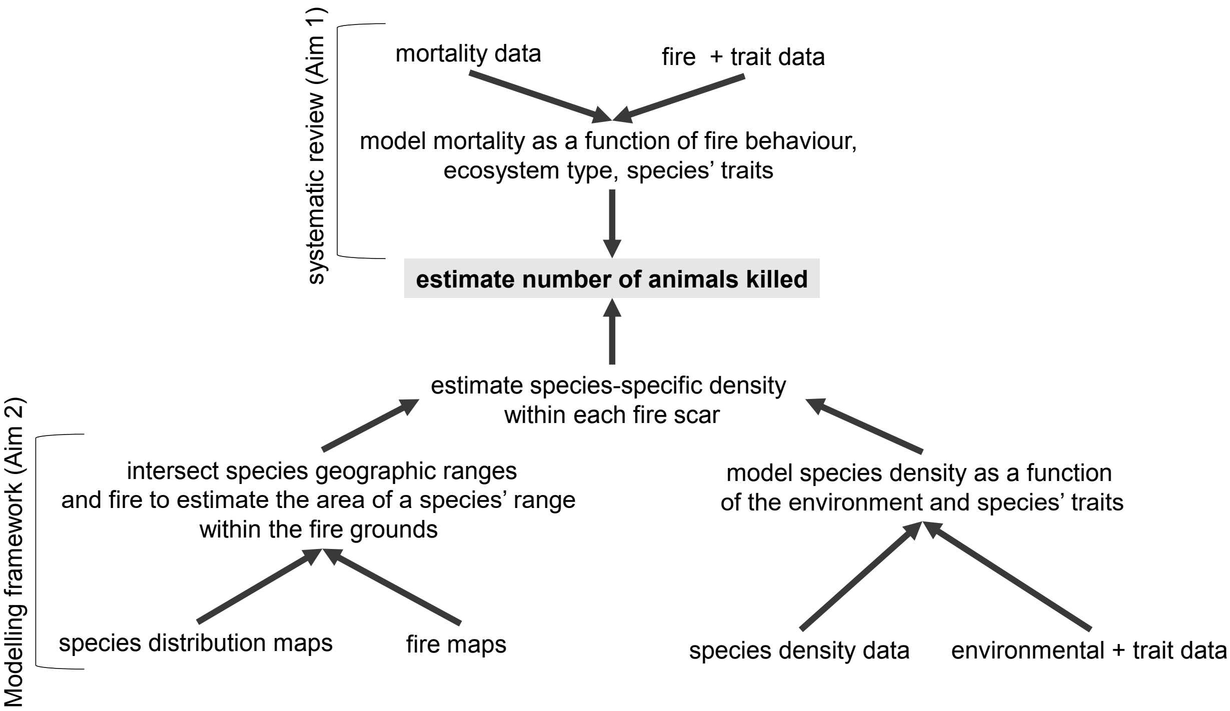


Figure 1: Our proposed framework for estimating the mortality of animals within fires using existing data. Species traits refers to body size and ecology.

Findings

We assessed 31 studies investigating 43 instances of the direct impacts of fire on wildlife mortality that spanned three continents (Africa, North America, and Oceania; Fig. 2 & 3a) and nearly four decades (1984–2020; Fig. 3a). Although studies that tracked the direct impacts of fire on wildlife mortality have increased through time (Fig. 3a) and all terrestrial vertebrate classes have been studied (Fig. 3b), there was a clear geographical bias in studies (Fig. 2 & 3a). The vast majority of studies were conducted in either the US (North America) or Australia (Oceania) (52% and 42%, respectively), and there were only two studies from African countries. In Australia, between 1996 and 2018, there were 13 studies of 21 instances of the direct effects of fire on the mortality of 13 native species (Fig. 3a). We were unable to detect any studies of the direct impacts of fire on the mortality of animals from Asia, Europe, or South America, despite there being vast fire-prone regions across these continents.

Most studies focussed on the direct effects of fire on mammals and reptiles (53% and 30%, respectively; Fig. 3b), with considerably less focus on birds and amphibians (12% and 5%, respectively; Fig. 3b). In Australia, the vast majority of studies have focused on the direct effects of fire on the survival of mammals (70% of Australian studies), with substantially less focus on birds and reptiles (15%, respectively). To date, there have been no studies investigating the direct effects of fire on the mortality of Australian amphibians. Globally, the families most frequently studied were Muridae (rodents; 5 instances) and Viperidae (vipers; 5 instances). Only five species (16%) had the direct impacts of fire on their mortality assessed in multiple studies, whereas 26 (84%) species were studied only once (Fig. 4). There was an enormous range in the body sizes of the animal species tracked across all studies, from tiny 8 gram red-backed fairy-wrens (Malurus melanocephalus) (Murphy *et al.* 2010; Sommer *et al.* 2018) to the world's largest terrestrial animal—the 4400 kg African bush elephant (*Loxodonta africana*) (Woolley *et al.* 2008).

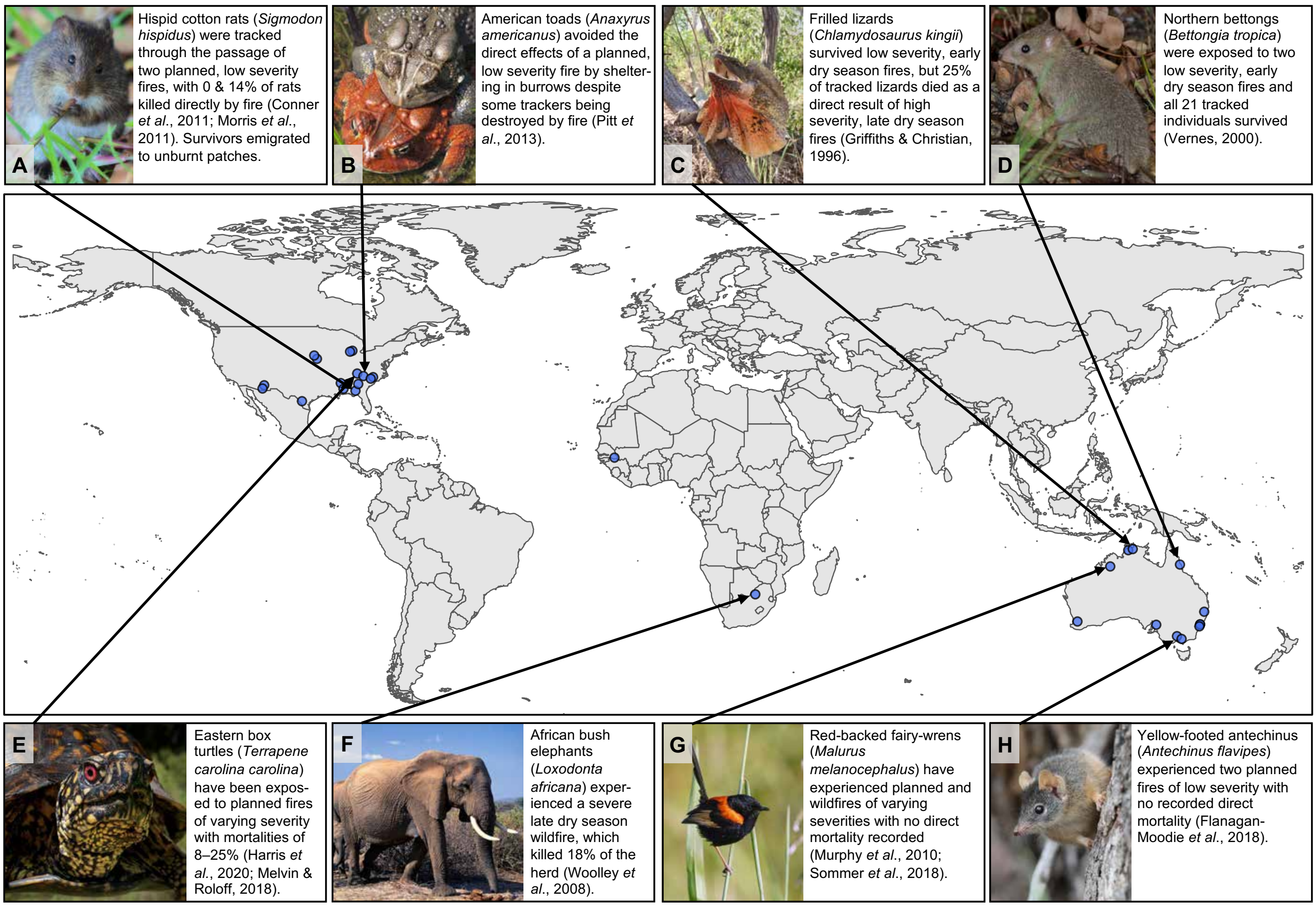


Figure 2. Global map of study locations. Species-specific examples of the direct effect of fire on animal mortality appear in boxes. Photograph credits: (A) James Leon Young CC BY-SA 2.0; (B) Vicki's Nature CC BY-NC-ND 2.0; (C) Alana de Laive; (D) Stewart Macdonald; (E) Brookhaven National Laboratory CC BY-NC-ND 2.0; (F) flickrfavorites CC BY 2.0; (G) David Cook Wildlife Photography CC BY-NC 2.0; (H) patrickkavanagh CC BY 2.0.(Griffiths & Christian 1996; Vernes 2000; Pitt et al. 2013; Flanagan-Moodie et al. 2018; Melvin & Roloff 2018; Harris et al. 2020)

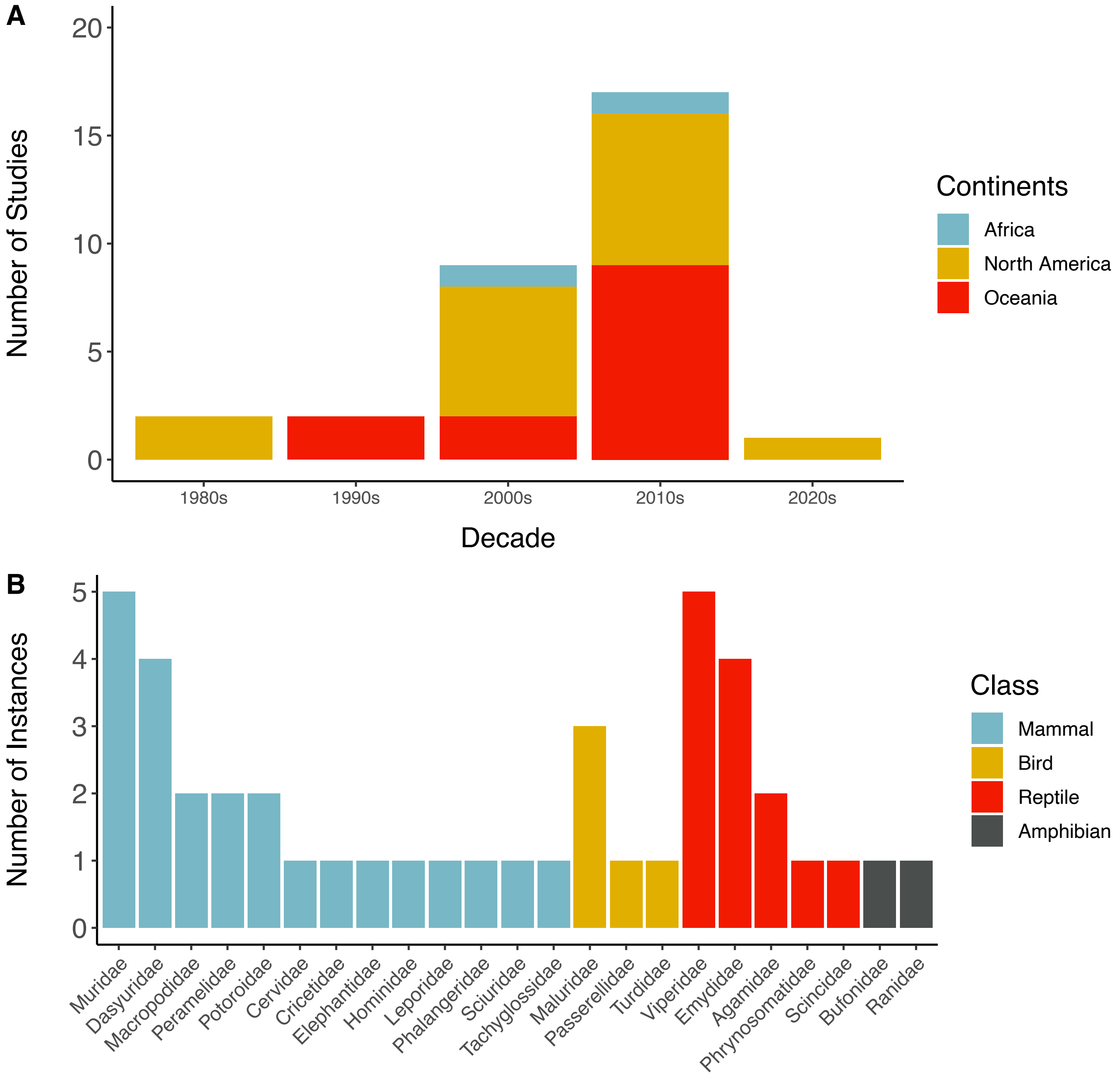


Figure 3. (a) Number of studies in the systematic review dataset (total 31) published per continent, per decade; and (b) number of instances that a species from each family grouped by animal class appeared in a study in the systematic review dataset.

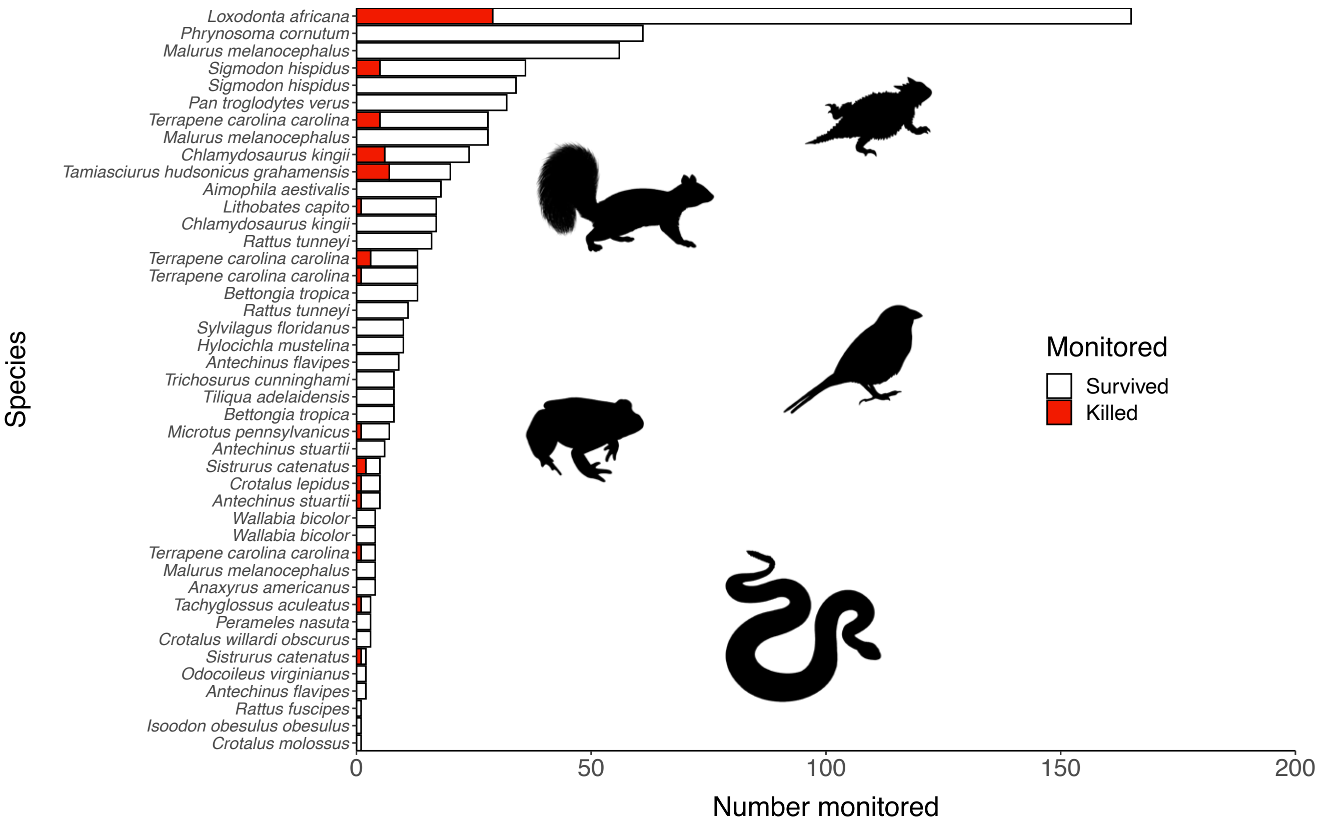


Figure 4. Direct effects of fire on the mortality of wildlife showing proportion killed by fire in each instance. Species that appear multiple times reflect multiple studies, or multiple instances, where the direct impact of fire was observed.

The direct impacts of fire on animal mortality have been investigated in seven of the 14 global terrestrial biomes (taken from Olson *et al.* 2001). We found examples of the direct effects of fire on the mortality of wildlife for planned fire and wildfire, and mild fire and severe fire (Fig. 5). Although many terrestrial biomes have been studied, most investigations were of instances of planned and mild fire in temperate broadleaf and mixed forests (42% of instances; Fig. 5). There was a bias towards studying the effects of planned (81%) and mild (70%) fire on wildlife mortality, with comparatively few instances of the effects of wildfire (19%) and severe fire (30%) (Fig. 5): this may be because planned fires allow researchers to plan and undertake the pre-fire preparation of animals to be tracked.

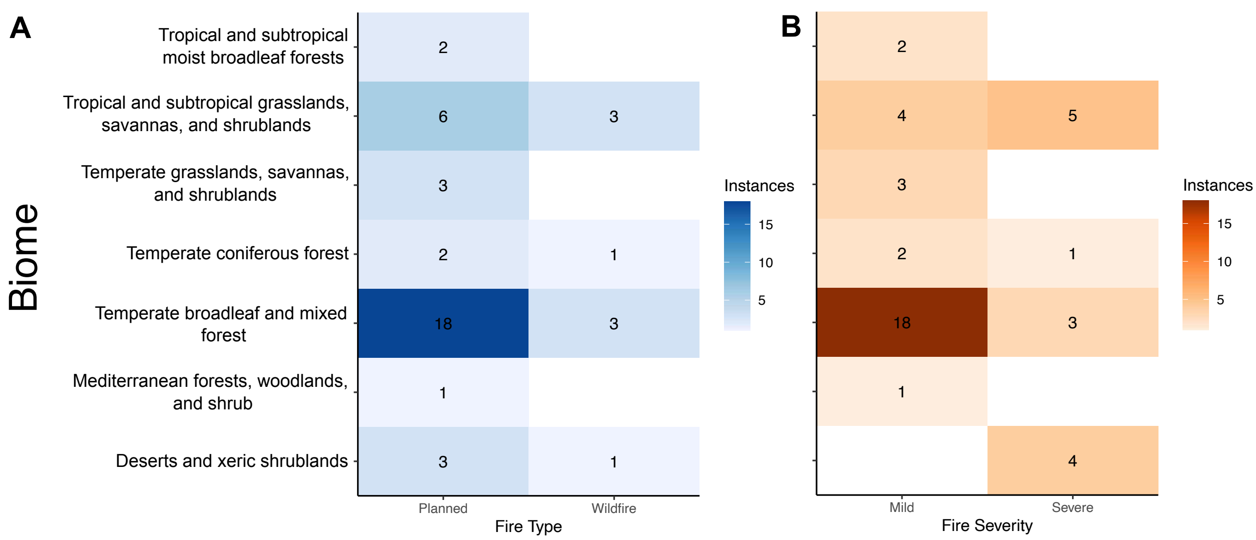


Figure 5. Counts of the number of instances (A) a fire type (planned or wildfires) and (B) a fire severity (mild or severe) was studied in each biome. Biomes are taken from Olson et al. (2001).

Although sample sizes of animals monitored through the passage of fire tended to be fairly small (53% of instances monitored fewer than 10 individuals), the majority of studies (65% of instances) recorded no direct mortality caused by fire (Fig. 4). The relatively small number of animals tracked in most studies likely reflects the labour-intensiveness and logistical difficulties inherent in tracking the movements of individual animals in the wild. Additionally, the tracking of wild animals via VHF and GPS can be financially demanding—in terms of both the technology and person hours required. This may also help to explain why we encountered a geographical bias away from many fire-prone regions within developing countries.

After removing studies that tracked very few animals (< 5 animals), we retained 29 instances of the direct effects of fire on mortality. Generalised linear mixed models revealed no apparent effects of fire type, body mass, ecology, or animal class on the direct effects of fire on animal mortality. In some cases, however, this lack of relationships may reflect the small sample size of our study (i.e., $n = 29$), rather than a genuine lack of effect. Despite the small sample size, a significant effect of fire severity on animal mortality was observed ($F_{1,28} = 5.7$, $p < 0.05$; Fig. 6), with a greater predicted proportion of animals dying in severe fires (mean mortality [95%CI] = 7% [2–21%]) than mild fires (mean mortality [95%CI] = 2% [1–7%]). Across all studies, our model estimates that an average of 3% (1–9%) of monitored animals died during the fires in our systematic review.

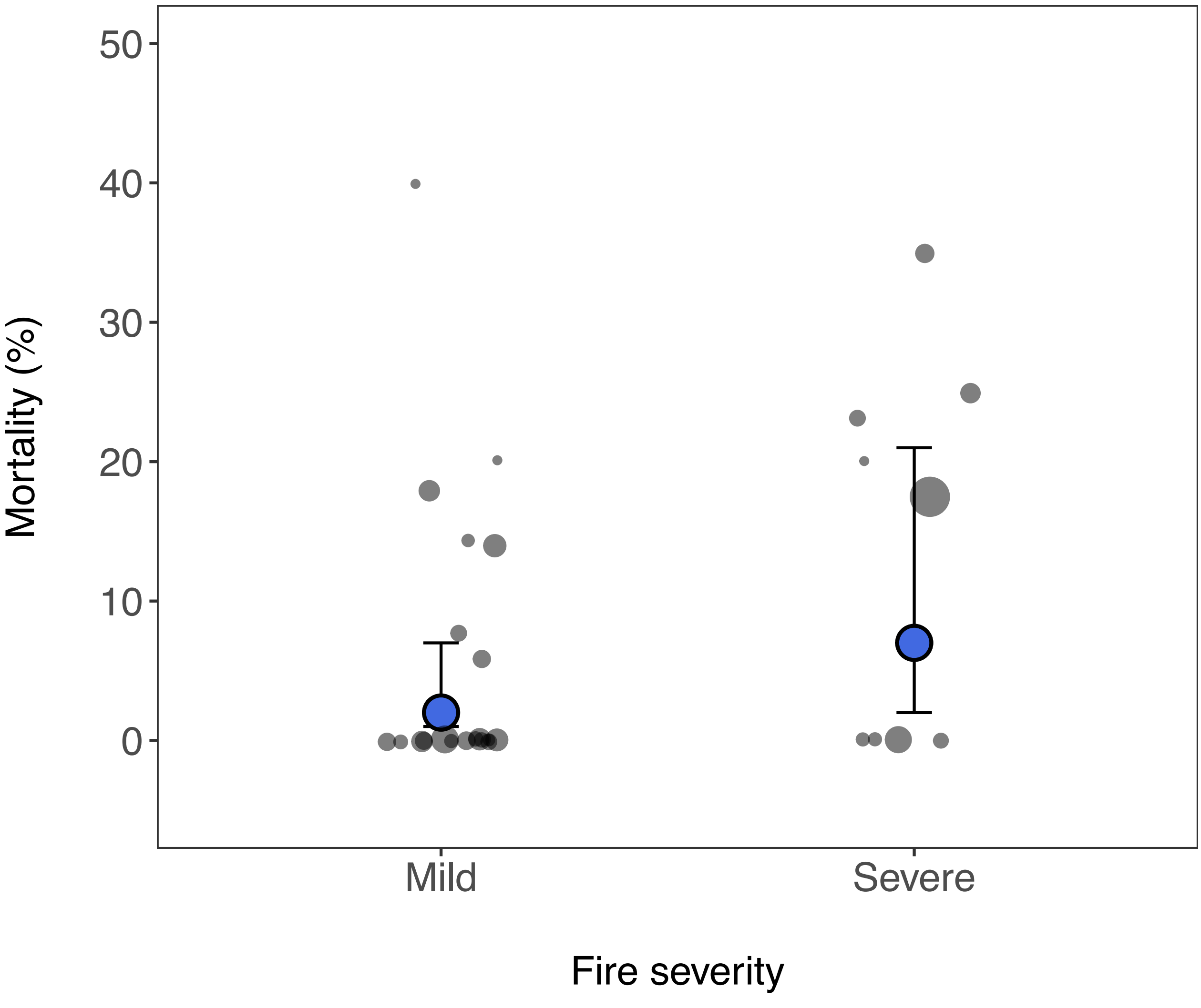


Figure 6. Mean predicted mortality rate (95%CI) of wildlife exposed to mild and severe fires. Only studies that monitored five or more individuals through the passage of fire were included. Black dots represent observed direct effects of fire on animal mortality with size of circle representing the number of animals monitored.

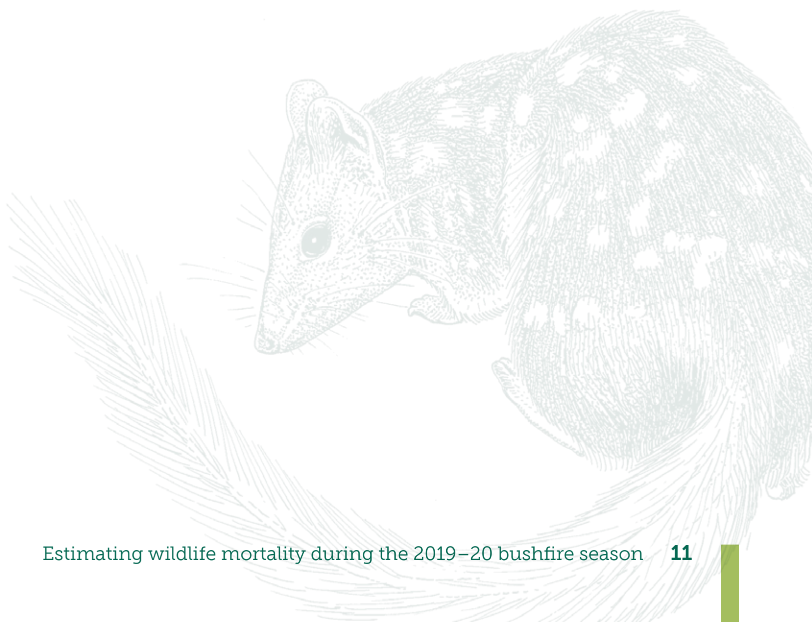
Discussion

Although our primary objective was to predict mortality rates for very severe wildfire—such as those experienced during the 2019–20 Australian megafire—we came across only one study that documented the mortality of animals during a megafire (i.e., a fire over 100,000 hectares), which measured fire-induced mortality of a single species (Banks *et al.* 2012). This highlights a pivotal gap in our understanding of how fire affects animal mortality. In 2009, Banks *et al.* (2012) had attached VHF transmitters to eight mountain brushtail possums (*Trichosurus cunninghami*) prior to the unexpected arrival of the Black Saturday megafires in Victoria. Surprisingly, despite the extreme severity of this uncontrolled fire, no direct mortality of possums was recorded in this study. Presumably, these possums avoided fire-driven mortality by sheltering in deep tree hollows that reduced their exposure to extreme heat. This finding, however, highlights an important trend in the studies we assessed—most animals tracked through the passage of fire did not succumb to the flames (Fig. 4) and only a small percentage (3%) of any given population is predicted to be killed by a fire of any size. While there were a number of instances that demonstrated how profoundly some severe fires can impact animal populations via direct mortality (e.g., in a herd of 165 endangered African bush elephants, 29 (18%) died as a direct result of an uncontrolled wildfire in South Africa (Woolley *et al.* 2008)), it is becoming increasingly clear that many animals from fire-prone regions are able to detect and respond to fires to reduce their direct impacts (e.g., Doty *et al.* 2018; Stawski *et al.* 2015; Grafe *et al.* 2002; Álvarez-Ruiz *et al.* 2021). Additionally, species traits, such a mobility, home range size, reproductive mode, diet, and ecological attributes (e.g., fossorial, terrestrial, or arboreal) may be important determinants of post-fire persistence.

While many animals may survive the initial passage of fire, the post-fire environment presents novel challenges that may have significant effects on the persistence of local populations. For example, although most American hispid cotton rats (*Sigmodon hispidus*) survived the passage of fire, most of the monitored populations fled to nearby unburnt plots, and those that did not flee suffered increased predation pressure in the burnt plots (Conner *et al.* 2011; Morris *et al.* 2011). Similarly, although all monitored pale-field rats (*Rattus tunneyi*) survived the passage of both mild and severe experimental burns in northern Australia, mortality due to predation increased after fire, presumably due to loss of ground cover (Leahy *et al.* 2015). In most cases, the studies we assembled considered mostly immediate responses to fire, rather than survival rates in the weeks or months post-fire.

We were able to produce models that predicted the density of reptiles across the fire grounds. Our models showed that reptile densities were higher in more productive (i.e., higher net primary productivity) and warmer (i.e., higher annual temperatures) regions, whereas high elevation and more seasonal environments had lower reptile densities. The model was used to predict the density of reptiles within the path of the 2019–20 bushfires. Summing across all fires, this resulted in an estimate of 2.46 billion reptiles being within the path of the fire, although there was considerable uncertainty in the estimate (van Eeden *et al.* 2020). This approach could be used on other taxa but requires further validation from Australian field sites.

We were not comfortable converting this estimate of animals within the fire-grounds to an estimate of mortality on the basis of the systematic review due to the relatively small number of studies that have measured animal mortality in the field, especially given the very small number that have measured mortality during severe fires (n = 13) and megafires (n = 1). Our caution underscores how little we know about the extent to which large, severe fires impose mortality on animal populations. Any extrapolation from our findings—even for severe fires which we found incurred ~7% mortality—would likely be an underestimate due to the unprecedented nature of the 2019–20 fires, and the lack of mortality estimates from similar fires in our systematic review.



Implications for ecological management in fire prone landscapes

The primary implication of this study was that we know remarkably little about the direct effects of fire on animal mortality. While it would be relatively straightforward to increase our understanding of the impacts of planned fire on the direct impacts on wildlife, it is far more difficult to monitor the outcomes on animals of large, unpredictable and uncontrolled wildfires. The most obvious way to approach filling this knowledge gap would be to drastically increase the tracking of native wildlife, particularly in areas and times of severe wildfire danger. This is likely to be aided by advances in the technology for tracking animals (e.g., moving from VHF to GPS tracking), making the task cheaper and less logistically challenging.

Although our data are limited, the evidence suggests that most animals avoid mortality during fire, particularly during mild fires. Across all fire types, only 3% of animals were predicted to be killed by the fire. It is important to note, however, that this estimate only captures the direct effect of fire—typically mild fire—and not the longer-term mortality that can arise due to depredation, starvation, or dehydration that threaten animals in simplified post-fire landscapes. What this does suggest, however, is that conservation efforts that address the challenges faced by animals in the post-fire landscape could be extremely valuable in reducing the longer-term, indirect impacts felt by animal populations in the weeks, months and years following a fire event. Put simply, all is not lost after a fire—many animals survive, opening a window for conservation intervention aimed at reducing post-fire mortality. Efforts that reduce predation pressure, such as the addition of artificial refuges to the landscape and targeted invasive predator control, and those that replace resources consumed by fire, such as supplemental food and water stations and nest boxes, could be leveraged to reduce the vulnerability of populations of threatened species following severe wildfires.

Our finding that animal populations suffer fewer deaths during mild fire than severe fire is expected and highlights the importance of undertaking management actions to reduce fire severity. We now know that the severity of 2019–20 wildfires was unprecedented (Collins *et al.* 2021), driven largely by climatic conditions prior to, and weather conditions during, the megafires (Abram *et al.* 2021; Bowman *et al.* 2021). As hot, dry conditions become more prevalent in a warming climate, we can expect further megafires akin to the 2019–20 wildfires. Hence, taking action on climate change is the main mechanism by which we can curtail the wildlife toll of future unplanned fires.

There is an increasing need to understand what the outcome of fire in the landscape is for native wildlife. Although our ability to estimate the density of animals across and among landscapes is improving, our ability to predict the direct effects of fire on animal mortality remains crude. Nonetheless, we are beginning to realise that wildlife are not hapless victims in the face of incipient fire and, unlike those affected by habitat clearing, most animals appear to survive the direct effects of fire. Animals that have evolved in fire-prone regions, such as eastern Australia's temperate broadleaf and mixed forests and northern Australia's tropical and subtropical grasslands, savannas, and shrublands, have adaptive responses they can mount to reduce the direct impacts of fire (Nimmo *et al.* 2021). However, unprecedented fires, like the Australian 2019–20 megafires, may well push these adaptations to their limits and beyond. Studies of animal survival during the 2019–20 megafires are yet to emerge, but may reshape our understanding of animal survival during fire.

Management advice to help inform fire management planning and response

Our study demonstrates that we currently lack a detailed knowledge of the direct impacts of fire on wildlife. Despite this, a number of trends emerge which may be prove useful in the management of species and populations potentially imperilled by fire.

In general, few animals appear to die as a direct result of fire (3% on average across all fires), but severe fires kill more animals than mild fires (7% vs. 2%, respectively). Thus, reducing the severity of fire might reduce the immediate fatal impacts of fire on vulnerable wildlife. However, this will become increasingly difficult in a warming and drying climate. Input from fire scientists who specialise in the impact of land management (e.g., prescribed burning) on fire behaviour should be sought to provide evidence-based approaches to reducing the scale and incidence of severe fire.

Assuming that a relatively small proportion of animals die as a direct result of fire, conservation management efforts that address the challenges faced by animals in the post-fire landscape could be extremely valuable in reducing the longer-term, indirect impacts felt by animal populations in the weeks, months and years following a fire event. Many such interventions have been carried out in the wake of the 2019-20 megafires, providing a platform for rapid knowledge acquisition in relation to the efficacy of these interventions. These interventions include actions that reduce predation pressure, such as the addition of artificial refuges to the landscape and targeted invasive predator control, and those that replace resources consumed by fire, such as supplemental food and water stations and nest boxes, could be leveraged to reduce the vulnerability of populations of threatened species following severe wildfires. However, the effectiveness of these interventions is largely unknown and needs to be monitored to ensure they are sound conservation investments. Opportunities exist to trial these interventions in combination with prescribed burning activities, to further hasten knowledge acquisition.

Future research should focus on (i) quantifying animal survival during severe and megafires, and (ii) investigating the best-practice, habitat- and species-specific post-fire conservation measures to improve post-fire persistence in vulnerable species so that they can be enacted following the next major fire event.

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Ethics statement

This study was entirely desk-based, and ethics approval was not necessary.

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Eastern Box Turtle. Image: Brookhaven National Laboratory, CC BY-NC-ND 2.0

Further information:

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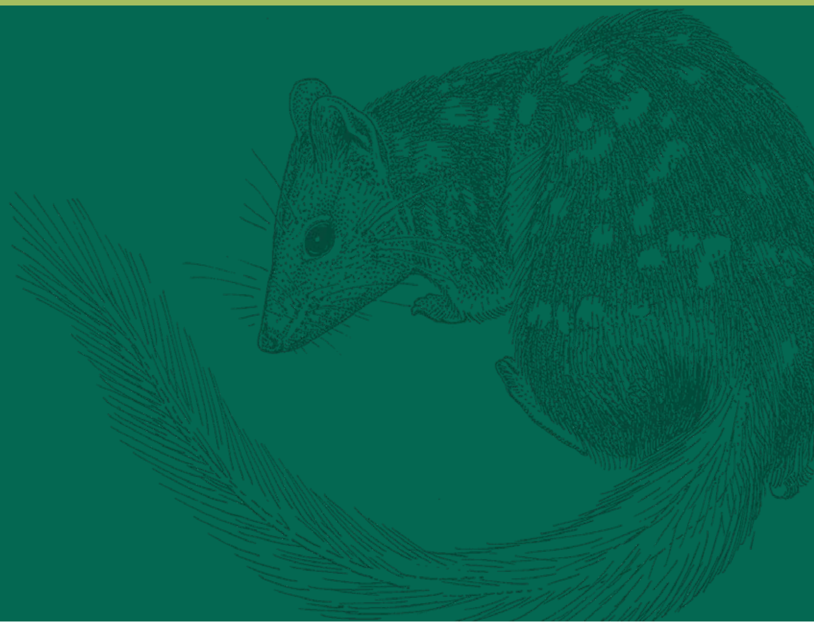

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