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Charles Darwin University

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# Design considerations for rapid biodiversity reconnaissance surveys and long-term monitoring to assess the impact of wildfire

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## Abstract

**Aims:** Reconnaissance surveys followed by monitoring are needed to assess the impact and response of biodiversity to wildfire. However, post-wildfire survey and monitoring design are challenging due to the infrequency and unpredictability of wildfire, an urgency to initiate surveys and uncertainty about how species respond. In this article, we discuss key design considerations and quantitative tools available to aid post-wildfire survey design. Our motivation was to inform the design of rapid surveys for threatened species heavily impacted by the 2019–2020 fires in Australia.

**Location:** Global.

**Methods:** We discuss a set of best practice design considerations for post-wildfire reconnaissance surveys across a range of survey objectives. We provide examples that illustrate key design considerations from post-fire reconnaissance surveys and monitoring programmes from around the world.

**Results:** We highlight how the objective of post-fire surveys drastically influences design decisions (e.g. survey location and timing). We discuss how the unpredictability of wildfire and uncertainty in the response of biodiversity complicate survey design decisions.

**Main conclusions:** Surveys should be conducted immediately following wildfire to assess the impact on biodiversity, to ground truth fire severity mapping and to provide a benchmark from which to assess recovery. Where possible, surveys should be conducted at burnt and unburnt sites in regions with historical data so that state variables of interest can be compared with baseline estimates (i.e. BACI design). This highlights the need to have long-term monitoring programmes already in place and be prepared to modify their design when wildfires occur. There is opportunity to adopt tools from statistics (i.e. power analysis) and conservation planning (i.e. spatial prioritization) to improve survey design. We must anticipate wildfires rather than respond to them reactively as they will occur more frequently due to climate change.

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## KEYWORDS

catastrophic disturbance, impact assessment, inventory, population viability, recovery actions, wildlife

## 1 | INTRODUCTION

Large, unplanned fires (hereafter “wildfires”) are predicted to increase in frequency, severity and duration in response to climate change (Boer et al., 2016; Goss et al., 2020). There have been recent examples of extreme wildfires in many ecosystems worldwide, such as the 2019 Amazon fires (Barlow et al., 2020), the 2020 Californian fires (Goss et al., 2020) and 2019–2020 fires in Australia (Nolan et al., 2020). Although fire is critical for shaping the distribution of plants and animals (Bowman et al., 2009), the immediate impact and response of biodiversity to wildfire is poorly understood (Whelan, 1995). This lack of knowledge is partly because wildfires are infrequent and unpredictable (Driscoll et al., 2010), which makes it difficult to plan for fire events ahead of time, limiting our ability to measure impact and recovery when they do occur.

Rapid inventories of plants and animals are critical for determining the impact of wildfires on biodiversity (Wintle et al., 2020). In the days and months following wildfire, rapid biodiversity surveys are crucial for assessing: mortality during and immediately after fire (Banks et al., 2011); the location and size of surviving populations that have otherwise suffered major losses; changes in the spatial extent of populations and how these relate to fire characteristics (Robinson et al., 2013); and environmental suitability confronting surviving populations in the short-term (Russell et al., 2003). Such information is essential for reassessing species' conservation status, prioritizing sites and species for targeted management responses and understanding species resilience to wildfire (Rouget et al., 2003). In the years to decades following wildfire, sustained long-term monitoring is then needed to track population recoveries, to measure management effectiveness and to assess cumulative impacts associated with any further disturbance events.

A challenge in wildfire response and planning is that effective and efficient surveys require careful design and implementation often within funding constraints (Legg & Nagy, 2006; Lindenmayer & Likens, 2018). Post-wildfire survey design can be challenging for several reasons. First, wildfires are highly stochastic and unpredictable often impacting biodiversity over large areas. Managers and scientists must test for, and estimate impact, after a fire has occurred against a backdrop of temporal and spatial variation in target populations. Second, surveys must be designed and implemented at short notice without the benefits of planning while minimizing the confounding effects of sampling and natural factors (Parker & Wiens, 2005). Third, wildfire can affect the behaviour and movement of both native and invasive species; survey designs that were appropriate prior to wildfire may not be as effective afterwards (Driscoll et al., 2012). These challenges may be especially magnified when wildfires are of exceptional extent, as surveys may then need to encompass many more species and sites.

There are many examples of effective post-wildfire survey and monitoring programmes that have assessed the impact and response of biodiversity (Banks, Knight, et al., 2011). However, to our knowledge there have been few attempts to synthesize key design considerations to inform future surveys (Southwell et al., 2020). Here, we review key steps for effective post-wildfire survey and monitoring design. We summarize common survey objectives, discuss how objectives influence subsequent design decisions and identify tools and approaches to improve survey design and planning. Our focus is on both rapid surveys to measure immediate impact of wildfire on biodiversity and long-term monitoring to quantify recovery. We provide examples from the scientific and grey literature to illustrate key design decisions. Finally, we discuss what can be done before wildfire to improve preparedness and planning.

Our motivation for this review was the 2019–2020 megafires in Australia. The fires burnt more than 10 million hectares over seven months with exceptional severity (Boer et al., 2020; Ward et al., 2020), directly affecting an estimated three billion mammals, birds and reptiles (van Eeden et al., 2020). During and after the fires, many agencies at the state and national levels were quick to conduct on-ground surveys, set priorities, identify knowledge gaps and initiate recovery responses (Geary et al., 2021; Wintle et al., 2020). However, few resources were available to inform key survey design decisions. General survey design considerations were needed at short notice on how, when and where to survey and establish long-term monitoring sites. We expect the principles discussed here will become increasingly important given the predicted increases in wildfire frequency and intensity with climate change (Boer et al., 2016; Goss et al., 2020).

## 2 | RECONNAISSANCE SURVEY AND MONITORING OBJECTIVES

We begin by defining the terms “reconnaissance survey” and “monitoring” in the context of wildfire. We assume that a “wildfire” is an unplanned fire impacting biodiversity across relatively large areas. We assume that a “reconnaissance survey” (otherwise called an “impact assessment” or “rapid inventory”) aims to document the immediate impacts of a wildfire on plants and/or animals and may or may not form a baseline to track post-fire recovery. It involves a study design in which sampling is undertaken as a single event in the weeks to months following wildfire, although how long a reconnaissance survey can be delayed is difficult to define. Recovery can then be defined as the reduction of impacts through time. We therefore define “monitoring” as repeated sampling of sites over time following wildfire to document both impact and recovery.

There are many reasons to conduct reconnaissance surveys following wildfire. No single survey design will be optimal across all objectives, and the ability to achieve an objective will be constrained by time limitations, feasibility, health and safety considerations, and the diversity of species to be considered. The available budget, in particular, will generally be the first major constraint to post-fire survey design. Limited funds for personnel and equipment will almost always mean that objectives must be achieved for the lowest cost or without exceeding an upper limit (Legg & Nagy, 2006; Lindenmayer & Likens, 2018). Objectives and constraints should be clearly identified early in the planning stage to ensure the most appropriate survey design. Objective setting is recognized as a major barrier to effective biodiversity monitoring (Lindenmayer & Likens, 2018) because it is difficult and has cascading effects on survey and monitoring design decisions (Legge et al., 2018). This is likely to become even more important in the context of wildfire as post-disaster emergency response is characterized by complexity, urgency and uncertainty (Parker & Wiens, 2005) and can involve multiple stakeholders and management organizations with differing values and beliefs.

Although there are few precedents where single fire events have caused complete extinction of plants or animals (Bradstock, 2008), a common objective of reconnaissance surveys is to determine whether entire populations or species were extinguished by wildfire. In this case, the goal might be simply to document survival or extinction. Confirming the persistence of species is most relevant for those that lack specialized fire-tolerant traits and have narrow distributions that might be completely burnt by a single wildfire. For example, the entire population of McDowall's Galaxias (*Galaxias mcdowalli*) is known to occur only in the headwaters of the Rodger River in East Gippsland, Victoria, Australia. The species' entire range was burnt by high-severity fire in 2014, which prompted reconnaissance surveys to determine whether the species had survived (Raadik & Nicol, 2015). Surveys detected individuals at the only accessible location in the river catchment, confirming species persistence. In contrast, a post-fire reconnaissance survey found that the only known population of the Banksia montana mealybug *Pseudococcus markharveyi* was extinguished in the 2019–2020 fires, and consequently, the species is now considered likely to be extinct (Moir, 2021).

Alternatively, reconnaissance surveys might aim to quantify the immediate impact of wildfire on state variables of interest, such as abundance, occupancy, survival, reproductive output or range size. Range size is of particular interest because it is a key factor influencing the listing status of species (Mace et al., 2008). Desktop analyses can be conducted relatively early in the planning stage if fire extent and species range maps are available. For example, Ward et al. (2020) intersected range maps of threatened species in Australia with fire extent shortly after the 2019–2020 wildfires and found that 70 nationally threatened species had at least 50% of their range burnt. Such analyses are useful for prioritizing species in most in need of reconnaissance surveys, monitoring and management (Gallagher et al., 2021; Legge et al., 2020). However, measuring the actual on-ground impact of wildfire on range size is much more difficult because surveys are required across the full extent of the

fire-affected range. This might be achievable for species with relatively narrow ranges but becomes increasingly difficult as both range size and fire extent increase. Populations are also likely to occur at variable densities across their extent, such that range loss may not be a good surrogate of proportional population loss.

When samples are collected repeatedly from in and around the burnt zone over a long period after wildfire, analysis of temporal dynamics may reveal both impacts and subsequent recovery. Well-designed reconnaissance surveys can therefore form the foundations of long-term monitoring programmes aimed at documenting population recovery. Long-term monitoring is critical for assessing the benefits of management interventions designed to aid recovery, such as predator suppression and habitat restoration. Monitoring will often be needed for extended periods to observe transitions in ecosystem composition, structure and function, or where subsequent fires may magnify the impacts of an initial fire event. This is particularly important in severely burnt landscapes where it can take decades for individuals to recolonize or for key structures to develop, such as tree hollows or large fallen trees (Lindenmayer et al., 2020).

### 3 | SURVEY DESIGN DECISIONS

#### 3.1 | Where to position sites

The survey objective will have cascading effects on survey design decisions, especially the location of sites. When the objective is to detect survivors, survey design does not necessarily require, but is helped by, comprehensive historical pre-fire records of a target species. Targeting unburnt refugia in and around the fire footprint where known populations existed, or locations predicted to provide highly suitable habitat, might increase the chances of encountering survivors.

When the goal is to measure change in state variables, such as occupancy or abundance, survey design becomes more challenging because counterfactual data (i.e. data in the absence of wildfire) are required for comparison (Thibault & Brown, 2008). If historical data are available from within the fire footprint, reconnaissance surveys can resample these locations to establish a “before–after” survey design. Before–after surveys assume the factors affecting the state variable of interest are in a steady-state equilibrium; that is, natural variation in these factors is similar both within and between before and post-fire sampling periods.

Where historical data are available in both burnt and unburnt habitats, “before–after–control–impact” (BACI) survey designs can be established (Green, 1979). BACI designs are most desirable because they can isolate the effect of wildfire from other environmental factors that might cause the state variable of interest to vary across space and time. Both BACI and before–after survey designs will not be possible for some taxonomic groups that are inadequately monitored, such as invertebrates (Saunders et al., 2021). Even when pre-fire data are available, careful consideration is still required (Smokorowski & Randall, 2017). For example, if few historical

samples are available, one does not know where they fit on the trajectory of natural variation in relation to post-fire samples. Further, if historical samples were taken many years before the impact event, uncertainty is increased because much may have happened in the interim. In addition, sites established prior to fires may include some sites that subsequently burnt, but this may not adequately sample the range of fire characteristics that influence fire impacts.

Alternatively, where historical data are not available, “control-impact” survey designs can be established to quantify the impact of wildfire. While these designs do not account for temporal variation among sites (Parker & Wiens, 2005), this limitation can be partly accounted for by replicating pairs of sites across geographically discrete clusters in the landscape (Banks, Dujardin, et al., 2011). Establishing new sites provides opportunity to stratify sites across continuous and discrete measures of fire characteristics, such as patch size, patch configuration or severity, to learn about how these factors influence impact and recovery (Lindenmayer et al., 2013). Wildfires generate a mosaic of patches across a landscape of varying fire severities, and survey designs should purposely consider the size and configuration of both low- and high-severity patches within the fire footprint using remotely sensed fire severity maps. For example, targeting smaller high-severity patches or patch edges might have a higher chance of detecting survivors than the interior of large high-severity patches (Steel et al., 2021). This is because the edge of high-severity patches potentially provides more resources within close proximity if low-severity habitat is nearby. Similarly, establishing sites in a buffer surrounding the fire footprint might detect individuals that dispersed away from the fire front.

There is an increasing body of evidence to suggest that the ability of species to withstand wildfire depends not only on habitat suitability but also on the condition of that habitat in the lead up to wildfire (Bowd et al., 2021). In particular, fire frequency and fire return interval will influence how species respond to wildfire (Lindenmayer & Taylor, 2020). This can be especially important for plants (Gallagher et al., 2021) where repeated fires can prevent effective regeneration and threaten long-term persistence by interrupting life cycles. For example, if fires occur too frequently they may prevent the replenishment of soil seed banks, restrict the resources required for plants to resprout, or not allow time for the juvenile recruits of resprouting species to become fire-resistant. Incorporating fire frequency in survey design and planning will become increasingly important as wildfires become more common around the world. For example, Lindenmayer and Taylor (2020) reported that tall forests in Victoria, Australia, had been affected by three wildfires since 2003, each burning more than 1 million hectares. This periodicity is many decades shorter than the natural mean fire return interval for the vegetation type (75 to 150 years).

### 3.2 | When to survey

Reconnaissance surveys should generally be initiated quickly in order not to squander conservation opportunities and so that

management can be allocated towards populations in most need (Rouget et al., 2003). However, there will be a trade-off in how quickly surveys can be initiated and the complexity of their design. There may not be sufficient time to collate historical occurrence records and spatial data layers. In some cases, reconnaissance surveys must be initiated quickly just to achieve an objective. For example, early surveys can identify dispersal and demographic characteristics driving reassembly dynamics. For example, Banks, Dujardin, et al. (2011) measured the abundance of small mammals along transects perpendicular to the edge of large, high-severity fires in Victoria, Australia, to understand the mechanisms driving recovery. They found that recovery was driven by survivors rather than by colonists from outside of the burn zone. Surveying immediately was critical to understanding reassembly dynamics.

In practice, the timing of reconnaissance surveys may be compromised by a range of regulatory, safety and logistical issues, as many otherwise ideal sites become inaccessible or unsafe in the immediate aftermath of a fire. Delaying reconnaissance surveys can limit what can be inferred about immediate impact and later recovery. If this delay is long, the results of reconnaissance surveys may include a mixture of direct and indirect fire-related impacts, recovery and changes unrelated to the fire. Unrelated post-event changes in the environment could mimic the impacts of fire, or recovery may mask the impacts that did indeed occur. It is possible that no effect may be found on a state variable of interest when there was an initial impact (type II error), or alternatively one might falsely conclude an apparent impact was due to wildfire (type I error). Unless one assumes that the system is in equilibrium and that it did not undergo changes between the fire and the sampling, there may be considerable uncertainty associated with the conclusions of delayed surveys.

Reconnaissance surveys should also consider seasonal variation in detectability of target species. Surveying immediately after wildfire may not be when a species of interest is most detectable. This presents a trade-off: managers can survey immediately when detectability might be low, risking a higher rate of false absence, or delay surveys to periods of highest detectability (such as during the breeding season), risking continued exposure of populations to post-fire threats (Leahy et al., 2015; Russell et al., 2003). The advancement of new technologies, however, such as camera traps and audio recorders that allow for continued data collection over long periods of time might go some way to resolving these design issues.

### 3.3 | Choice of sampling methods

The choice of sampling method(s) will be influenced by the survey objective, state variables of interest, target species, financial cost, observer experience and data compatibility across space and time. Data compatibility is critical for survey designs relying on historical data, although it is also relevant when multiple organizations survey concurrently in different regions. Lyon and O'Connor (2008) provided a useful example of maintaining data compatibility when assessing the impact of wildfire. They measured the effect of sediment

run-off on fish populations at 8 control and 12 impact sites following wildfire in Victoria, Australia. The post-fire sites were purposely located in regions with historic data and surveyed with comparable methods so that fish abundance and diversity could be compared across pre- and post-fire periods.

Although maintaining sampling consistency should be a priority, there might be instances where the post-fire environment or changes in the behaviour of species result in the choice of less preferred sampling methods (Driscoll et al., 2012; Whelan, 1995). For example, snorkelling is one way to detect freshwater turtles (Chessman et al., 2020), but this technique may become ineffective if sediment run-off decreases water visibility following fire. In another example, Driscoll et al. (2012) suggest that manual searches or stationary visual surveys of reptiles might perform better in post-fire environments compared with pitfall traps because trapping becomes relatively ineffective when population densities are low. Thus, the likely performance of preferred sampling methods in a post-fire environment should be given thought during survey design.

## 4 | SURVEY DESIGN CHALLENGES

### 4.1 | Data availability

A major challenge of before–after or BACI survey designs is the paucity of long-term monitoring data for most species and knowing where surveys occurred pre-fire. There are marked biases in existing biodiversity monitoring programmes, with disproportionately low rates of monitoring for plants and invertebrates relative to vertebrates (Lavery et al., 2021). If such biases are not addressed, they will compromise the capability to use fire reconnaissance surveys to assess fire impacts for large components of biodiversity. Further, long-term monitoring data are usually stored in institutional silos and not readily available for conservation planning (Legge et al., 2018). For example, in Australia there are very few comprehensive databases containing distributional data for native species with the exception of atlas records. Hence, when assessing fire impacts, data must be aggregated from multiple sources, such as atlas records and state agency databases. In the face of an emergency, this exercise is time-consuming and delays on-ground action.

Given the critical role that fire severity mapping plays in reconnaissance survey design, national facilities for collating and producing near-real-time information on wildfires are needed. For example, a lack of timely data on fire extent and severity hampered a rapid response to the 2019–2020 wildfires in Australia (Legge et al., 2020). Fire severity mapping was conducted by each state and territory government but using alternative methodologies that generated incompatible maps with varying accuracy and resolutions. This meant that maps were not available across jurisdictional boundaries at the scale relevant to the fires and range of many vulnerable species. Initially, the Commonwealth Government merged these separate datasets to create a National Indicative Aggregated Fire Extent Dataset (DAWE, 2020b). However, this dataset only mapped fire extent and

not fire severity or unburnt refugia within the fire footprint. It was not until 6 months after the wildfires that high-resolution fire severity mapping was available at a national scale, limiting rapid response efforts and planning (DAWE, 2020a).

### 4.2 | Survey effort

An important design consideration is the number of sites needed to detect impact and/or recovery. Statistical power is defined as the probability of rejecting the null hypothesis given that the null is false and supporting the alternative hypothesis that a change has occurred (Taylor et al., 2007). One challenge of post-fire surveys is that in before–after comparisons, the number of historical data points is often limited. This increases the estimate of error used in statistical tests and uncertainty of conclusions. Because the consequences of failing to detect actual effects of wildfire may be great, the likelihood of type II errors remains an important concern. There are many tools for assessing the statistical power of detecting impact or population trends (Guillera-Arroita & Lahoz-Monfort, 2012). For example, Wood (2021) explored how the number of sites (i.e. 15, 30 or 60 sites) influenced power across a range of plausible impact and recovery scenarios, and thus how many pre- and post-wildfire sites are needed to detect likely impacts on wildfire.

Reconnaissance surveys should account for the chance that species are not detected at sites even though they have survived and are present (MacKenzie et al., 2002; Wintle et al., 2005). Failing to detect survivors will result in false absences (Garrard et al., 2008), which can lead to type II errors. The rate of false absences can be reduced to acceptable levels by determining the minimum level of survey effort given estimates of detectability. Another challenge of post-wildfire survey design is that detectability is rarely known for target species, and when available, it is often only relevant to unburnt habitat. The degree to which detectability changes immediately following wildfire is not clear for most species, making survey design difficult (Whelan, 1995). On the one hand, there is evidence to suggest that detectability might increase due to increased activity and movement of individuals (Cherry et al., 2018; Driscoll et al., 2012). On the other hand, there is reason to suggest it might decrease as density, movement and/or behaviour of individuals is reduced (Hodson et al., 2010; Nimmo et al., 2019). For example, frequent use of torpor has been documented in *Antechinus* species following wildfire as a way of decreasing activity and saving energy, potentially lowering rates of detection (Matthews et al., 2017).

### 4.3 | Measuring threats

Animals and plants that survive fire are faced with an elevated risk of mortality afterwards due to increased exposure to threats, such as changes in levels of competition and predation from introduced and invasive species (Christensen et al., 1981; McGregor et al., 2016). Threats acting on plants, such as herbivory, disease, weeds and

post-fire erosion, may be amplified following wildfire (Gallagher et al., 2021). Similarly, aquatic species can be impacted post-fire by altered flow regimes, increased water temperatures and increased sediment loads and run-off, particularly after heavy rainfall (Lyon & O'Connor, 2008). Predation by native and introduced species can also become more acute following fire (Russell et al., 2003). For example, densities of foxes and cats can increase following fire as individuals immigrate from surrounding unburnt habitat (Davies et al., 2017; McGregor et al., 2016; Stobo-Wilson et al., 2020), but decrease in other cases (Arthur et al., 2012; Catling et al., 2001). Comparison with baselines, either from historical data or from unburnt sites, is needed to determine whether the intensity of threats is impacted by wildfire. Decisions about how, where and when to survey post-wildfire for target species also apply to threats, further complicating survey design.

## 5 | OPPORTUNITIES AND SOLUTIONS

### 5.1 | Species distribution modelling and spatial prioritization

There is opportunity to adopt modelling and conservation spatial planning tools to improve post-wildfire survey design. There are surprisingly few examples where species distribution models (SDMs) have informed where to survey, presumably because such models can be data-intensive and take too long to build. In one example, Bosso et al. (2018) mapped the pre-fire occurrence of 12 species of bat using SDMs and used these maps to evaluate how much of their habitat was affected by fire. More recently, Andrus et al. (2021) combined SDMs with fire severity maps to inform post-fire survey design and management decisions. They developed a refugium index to assess the value of unburned areas for wildlife habitat using a flexible multi-scale fuzzy logic. Using the northern spotted owl (*Strix occidentalis caurina*) as an example species, they identified relatively higher versus lower quality fire refugia for nesting/roosting habitat in 15 fires that each burned >400 ha of spotted owl nesting/roosting habitat in the eastern Cascade Mountains, USA.

While fire severity maps and SDMs can inform where to establish sites, limited budgets will constrain the number of sites that can be surveyed. There is opportunity to adopt conservation planning and spatial prioritization tools to identify regions for reconnaissance surveys and monitoring. Spatial prioritization tools are commonly used to address questions such as where to establish conservation reserves, where to target habitat restoration or where to establish new developments while ensuring complementarity, adequacy and representativeness (Margules & Pressey, 2000; Scott et al., 1993). Such tools will likely become more important as the size of wildfires increase and because they have the capacity to explicitly include spatial layers, such as fire frequency and threats (Geary et al., 2021). There are surprisingly few examples where spatial prioritization tools have informed the design of

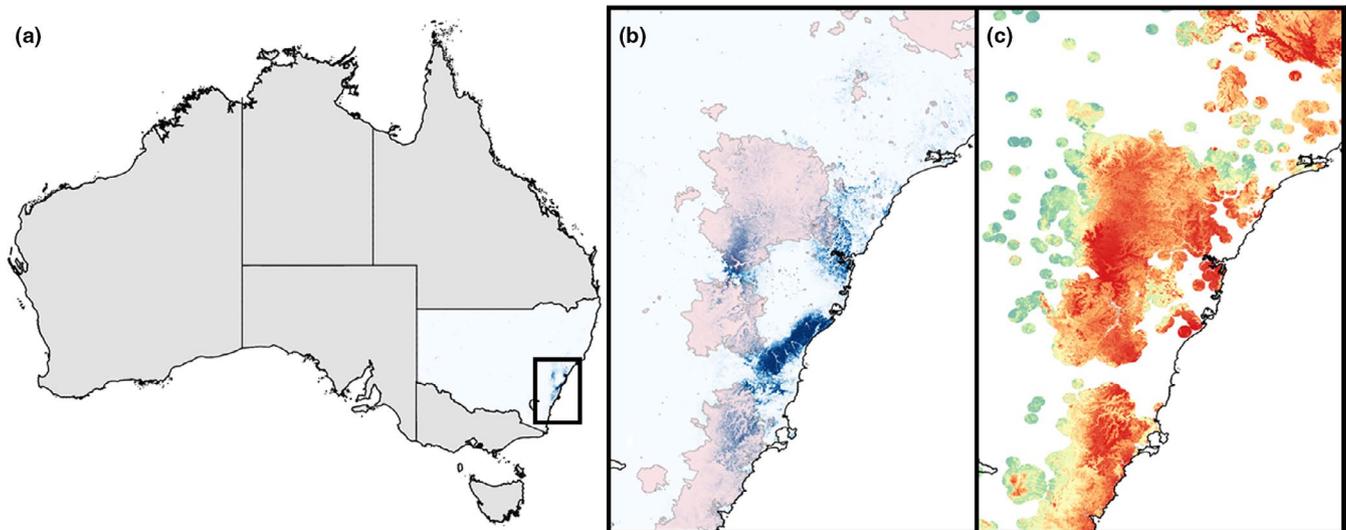
post-wildfire surveys (Geary et al., 2021; Southwell et al., 2020) despite optimization approaches increasingly being used to design large-scale biodiversity monitoring networks (Amorim et al., 2014; Carvalho et al., 2016; Moran-Ordóñez et al., 2018). A recent example that integrated SDMs and fire severity maps using spatial prioritization tools to inform post-fire survey design in presented is Box 1 and Figure 1.

### 5.2 | Occupancy-detection modelling

Given uncertainty surrounding detectability of most species in post-wildfire environments, surveys should ideally sample sites repeatedly (or at least a subset of sites) so that detection probabilities can be estimated with occupancy-detection models (MacKenzie et al., 2002). This will provide some quantification of detectability and guide whether survey effort should be adjusted under any ensuing monitoring programme (Garrard et al., 2015). Single-season occupancy-detection models can be extended to a multi-season framework (Royle & Kery, 2007), which may be particularly useful for understanding extinction and colonization dynamics driving recovery. For example, Jones et al. (2019) fitted dynamic occupancy-detection models to pre- and post-fire monitoring data for the northern spotted owl (*Strix occidentalis caurina*) to assess impact of the 2014 King Fire in the western USA. Such models quantify extinction and colonization dynamics, but can also model temporal changes in detectability, which is likely to be important as habitats and the behaviour of species return to pre-fire conditions.

#### BOX 1

Southwell et al. (2020) developed species distribution models for 92 vertebrates identified by experts (Legge et al., 2020) as likely to have been most affected by the 2019–2020 megafires in Australia. After predicting where these species occurred in the landscape before the fires, they combined this information with high-resolution fire severity maps in the spatial tool, Zonation (Lehtomäki & Moilanen, 2013), to prioritize regions in the landscape for reconnaissance surveys. The optimal survey locations were positioned in and around the fire footprint to ensure equal representation across all priority species and fire severity classes. The authors also mapped the location of reconnaissance surveys already underway, and “locked” these locations into the spatial prioritization so that the optimal locations for new surveys were selected to complement existing survey efforts. Their approach provided a framework for deciding where to survey after wildfire and informed the design of government-funded surveys.



**FIGURE 1** Predicted pre-fire habitat suitability for the broad-headed snake (*Hoplocephalus bungaroides*) in Australia (a) and NSW (b) developed to inform post-fire reconnaissance surveys after the 2019–2020 megafires. Dark blue shading in (b) indicates areas of high predicted habitat suitability; pink shading represents the fire extent. Panel (c) illustrates the results of a spatial analysis that prioritized regions for new post-fire reconnaissance surveys for priority reptiles, with red shading indicating the highest priority areas for additional surveys. Further information on the species distribution modelling and spatial prioritization can be found in Southwell et al. (2020)

### 5.3 | Simulation and optimization

Simulation provides opportunity to resolve key design decisions and trade-offs ahead of time. For example, predictive fire simulation models could identify regions most likely to contain wildfires under climate change scenarios and potential refuges within the fire footprint (Berry et al., 2015). Such models could be coupled with simulations of the monitoring process to explore alternative designs and key trade-offs in survey design decisions and budgetary constraints (Southwell et al., 2019). There is often a trade-off between the number of sites surveyed and the time spent surveying sites (Einoder et al., 2018). Simulation can help understand the optimal allocation of effort between such actions for fixed budgets. For example, Smart et al. (2021) developed a spatially explicit simulation framework to explore optimal monitoring design following the 2019–2020 fires in Australia (Box 2). They estimated power to detect recovery in 45 species to pre-fire levels across a range of fixed budgets, and, for each budget, explored trade-offs between the number of sites, survey effort and survey frequency (Figure 2).

### 5.4 | Citizen scientists and data integration

The involvement of citizen scientists in post-fire surveys can increase the spatial and temporal resolution of sampling. For example, Kirchoff et al. (2021) and Rowley et al. (2020) provide recent examples where citizen scientists have recorded the occurrence of species after megafire over large spatial scales. However, data collected by volunteers are usually subject to observer and spatial

#### BOX 2

Smart et al. (2021) developed a spatially explicit power analysis framework for optimizing the design of biodiversity monitoring programmes to detect recovery of species following the 2019–2020 megafires in Victoria, Australia. Spatially explicit power analysis is particularly useful because it allows for the location, number and arrangement of monitoring sites to be explored, while accounting for spatial patterns in species distributions. Smart et al. (2021) collated species distribution models for 45 vertebrates most affected by the megafires in Victoria, Australia, and combined these models with remotely sensed maps of fire severity to optimize the location of monitoring sites in and around the fire footprint. They simulated a range of plausible recovery rates in species distributions over the next 15 years and, with estimates of detectability, simulated monitoring at control–impact sites to evaluate the statistical power of alternative monitoring design. They also developed a cost layer to determine the optimal allocation of resources for realistic budget scenarios.

bias, preventing what can be inferred about impact and recovery. The conventional approach to modelling in ecology is generally to model only one data type (Isaac et al., 2020). This is usually a choice between small quantities of structured data that might only cover a small footprint of a species range, or large quantities

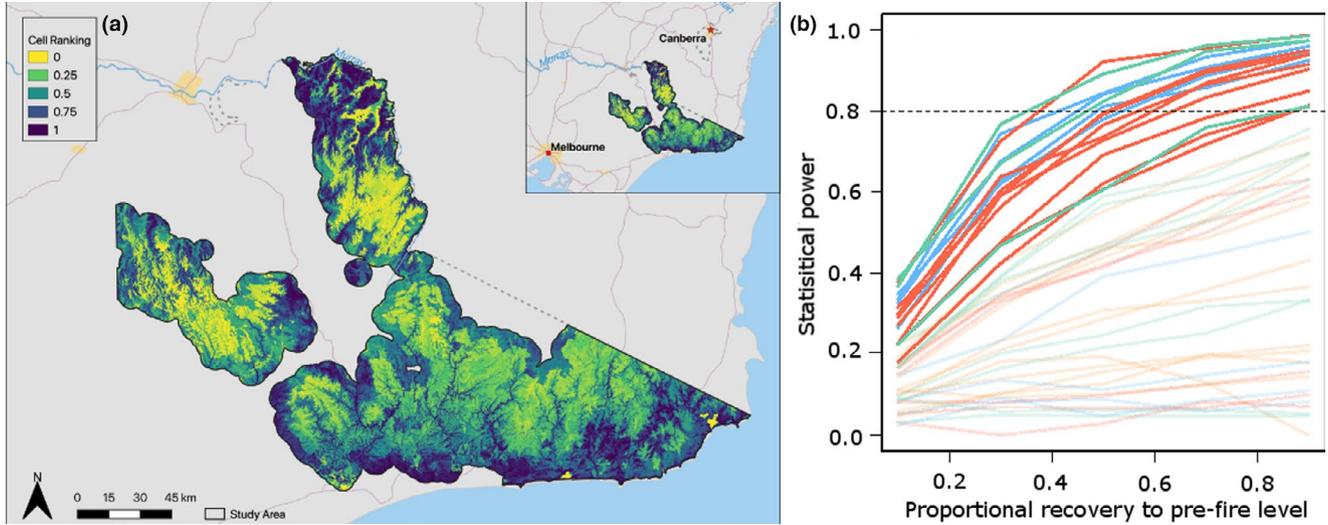


FIGURE 2 (a) High priority regions (purple) for long-term monitoring in and around the 2019–2020 wildfires in Victoria, Australia, and (b) the statistical power (y-axis) to detect recovery of 45 species to pre-fire levels (x-axis) over the next 15 years

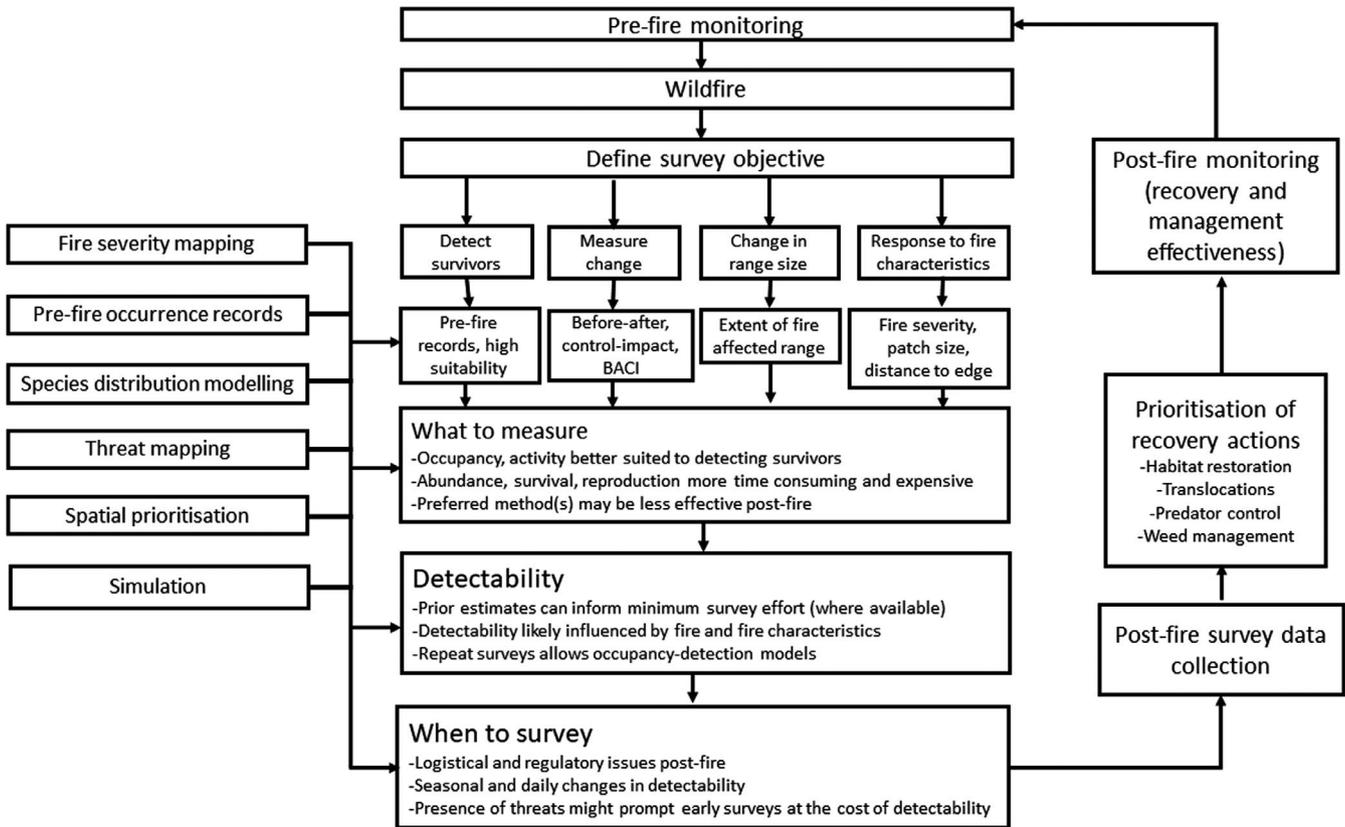


FIGURE 3 Key steps and design considerations for post-fire reconnaissance surveys and monitoring. The survey objective plays an important role in subsequent design decisions. The availability of comparable pre-fire monitoring data should also affect where, how, when and what to measure. Post-fire reconnaissance surveys should form the foundations for long-term monitoring, which can inform future reconnaissance survey design decisions

of unstructured data with increased coverage but substantial biases (Kindsvater et al., 2018). An emerging field in ecology is the use of flexible statistical models that explicitly account for differences in data type and quality, as well as sources of uncertainty

(Isaac et al., 2020). Analysis of multiple datasets in a single statistical framework could substantially improve species assessments of impact and recovery because more can be made from existing survey data.

## 5.5 | Preparedness and adaptive monitoring

Key to effective post-wildfire survey design is for ecologists and decision-makers to plan ahead so they are better prepared for when wildfires do inevitably occur. Wildfires should not be treated as surprise events; rather, we need to recognize that they will occur again in future. There has been little strategic prioritization for the protection or management of key populations or critical habitat before or after disturbances occur. Instead, recovery actions are implemented reactively based on expert opinion rather than empirical evidence. To inform effective mitigation of disturbances, there is an urgent need to synthesize existing biodiversity data, predict responses of biodiversity to recovery actions and learn from the outcome of past events (Figure 3). National or continental databases of biodiversity surveys, species distribution models, threat maps and responses to disturbances or disasters would assist post-fire planning (Wintle et al., 2020). Perhaps most importantly, long-term monitoring programmes must already be operating across a range of taxa (with ready access to site locations and metadata), and decision-makers must be willing to adapt and modify these programmes to learn about the impact of wildfire when it does occur (i.e. adaptive monitoring) (Lindenmayer & Likens, 2009). Organizations responsible for post-wildfire survey design should have a fast and effective decision-making process to navigate survey design considerations and ensure key issues are resolved ahead of time. In addition, funding programmes should be available that facilitate rapid research responses to major natural disturbances so that learning opportunities are not lost or only partially realized (Lindenmayer et al., 2010).

Surveys should be conducted immediately following wildfire to assess the impact on biodiversity and to ground truth fire severity maps. Where possible, surveys should be conducted at burnt and unburnt sites in regions with historical data so that state variables of interest can be compared with baseline estimates (i.e. BACI design). There is opportunity to borrow tools from statistics (i.e. power analysis) and conservation planning to improve survey and monitoring design. Better tools are needed to improve predictions of pre-fire habitat condition and where unburnt refugium patches might occur after a fire event. Importantly, we need to plan ahead for wildfires; they will occur more frequently due to climate change. We must have long-term monitoring programmes already in place and be prepared to modify their design when unplanned fires occur.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest.

### PEER REVIEW

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### DATA AVAILABILITY STATEMENT

Data are available at: <https://www.environment.gov.au/biodiversity/bushfire-recovery/research-and-resources>

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#### BIOSKETCH

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