Austral Ecology A Journal of ecology in the Southern Hemisphere

Ecological Society of Australia

Austral Ecology (2023) **48**, 31–40

Using citizen science to measure recolonisation of birds after the Australian 2019–2020 mega-fires

JOSHUA S. LEE,*[1] COREY T. CALLAGHAN[1,2] AND WILLIAM K. CORNWELL[1,2]
[1]*Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, UNSW Sydney, Sydney, New South Wales, 2052, Australia (Email: josh.lee2415@gmail.com); and* [2]*Ecology & Evolution Research Centre, School of Biological, Earth and Environmental Sciences, UNSW Sydney, Sydney, New South Wales, Australia*

Abstract Large and severe fires ('mega-fires') are increasing in frequency across the globe, often pushing into ecosystems that have previously had very long fire return intervals. The 2019–2020 Australian bushfire season was one of the most catastrophic fire events on record. Almost 19 million hectares were burnt across the continent displacing and killing unprecedented numbers of native fauna, including bird species. Some bird species are known to thrive in post-fire environments, while others may be absent for an extended period from the firegrounds until there is sufficient ecosystem recovery. To test for systematic patterns in species use of the post-fire environment, we combined citizen science data from eBird with data on sedentism, body size, range size and the specialisation of diet and habitat. Using generalised additive models, we modelled the responses of 76 bird species to the 2019–2020 Australian mega-fires. Twenty-two species decreased in occurrence after the fire; 30 species increased; and no significant effect was found for the remaining 24 species. Furthermore, diet specialists, and birds with smaller body sizes and range sizes were less likely to be found in burnt areas after the fire event compared to before, a result which generates testable hypotheses for recovery from other mega-fires across the globe. Being displaced from the firegrounds for an event of this geographic magnitude may have severe consequences for population dynamics and thus warrant considerable conservation attention in pre-fire planning and in the post-fire aftermath.

Key words: bird traits, bushfire, citizen science, eBird, post-fire recovery.

INTRODUCTION

The 2019–2020 Australian bushfire season was one of the largest and longest on record (Filkov *et al.* 2020; Nolan *et al.* 2020) affecting almost 19 million hectares (Boer *et al.* 2020; Filkov *et al.* 2020). It is estimated that almost 3 billion native vertebrates will have perished or been displaced because of the 2019–2020 mega-fires (DPIE 2020a; van Eeden *et al.* 2020). In the wake of these immense disturbance events it is important to understand the process of ecosystem recovery to implement effective conservation actions. Birds are useful indicators of environmental health since bird communities may reflect the composition of food and habitat resources in an environment (Gregory *et al.* 2003; Gregory & Strien 2010; Eglington *et al.* 2012; Ainsworth *et al.* 2018; Davies *et al.* 2019). Furthermore, birds are vital agents of recolonisation in a post-fire landscape due to their high mobility and reintroduction of seed from nearby unburnt patches (Gill 1996; Cavallero *et al.* 2013; Pausas & Parr 2018). From a conservation and management perspective, predicting which bird species recolonise more rapidly and which might be at greater risk from fire is an important goal.

The massive geographic scale of this fire event means that a larger proportion of species' ranges have been affected compared to previous fire seasons (DPIE, 2020a). However, the scale of these fires also creates a challenge for gathering data on species recovery: data across this geographic scope are difficult to easily obtain. Moreover, data need to be collected quickly because many important post-fire processes occur soon after the event. One solution to this set of problems is mobilising volunteers through citizen science platforms (Kirchhoff *et al.* 2020) as survey effort can be accomplished at a speed and magnitude that would otherwise be impossible (McKinley *et al.* 2017).

Fire is a common and widespread process throughout the continent of Australia (Bradstock *et al.* 2002) making fire resilience common in the life histories of many plants and animals (Purdie & Slatyer 1976; Cary *et al.* 2012). The post-fire environment, especially after severe fire, is generally devoid of many resources and habitat features (Loyn 1997a).

*Corresponding author
Accepted for publication July 2021.
[Correction added on 7 October 2021 after the first publication: Corresponding author's email address was updated.]

doi:10.1111/aec.13105

However, new resources are often created in the wake of fire events, making post-fire environments productive foraging grounds for some recolonising species (Pons & Prodon 1996; Loyn 1997b; Albanesi *et al.* 2014; Prowse *et al.* 2017; Pausas & Parr 2018). The heterogeneity of the burn, combined with the patchy and unpredictable nature of the resources in the post-fire environment may favour some feeding generalist species and disadvantage other species with very specific dietary requirements (Banks *et al.* 2011; Lindenmayer *et al.* 2011). Another key feature of the post-fire environment is the removal of vegetation that acts as cover for predation-sensitive species (LaManna *et al.* 2015). In large-scale fire events, where bird mortality and displacement are expected to be high, a species' dispersal ability may be important for recolonisation (Turner *et al.* 1998; Whelan *et al.* 2002; Robinson *et al.* 2014). Understanding how bird traits are associated with post-fire recovery allows for predictions about the impacts of future fires.

We had three main objectives: (i) to quantify the response of species occurrence as either increasing, decreasing, or no change in response to the 2019–2020 Australian bushfire; and (ii) to model species' fire responses against five potentially important bird traits (i.e. sedentism, body size, range size, and the specialisation of diet and habitat); and (iii) to investigate whether increased fire severity is associated with decreased bird recolonisation. We hypothesised that more effective post-fire recolonisation would be associated with larger body size, larger range size, increased mobility and utilisation of a larger number of food and habitat types. We also expected that birds would recolonise more quickly in less severely burnt fire areas.

METHODS

Bird occurrence data

We used the eBird citizen science database (Sullivan *et al.* 2009, 2014) to understand bird occurrences before and after the fires. eBird is a global citizen science project that enlists volunteer birdwatchers to submit bird observations to a database with >850 million bird observations globally. Citizen scientists can submit data as isolated species records or through complete checklists with survey effort information (e.g. time spent surveying, distance travelled) and spatiotemporal coordinates. A semi-automated approach to data quality is used where regional filters are set by local experts, and species or counts of species which exceed those filters need to be substantiated before being approved in the database (Wood *et al.* 2011).

We downloaded data (eBird Basic Dataset version ebd_relApr-2020) for Australia between 1 January 2010 and 1 May 2020. In order to account for potential biases associated with citizen science data (Bird *et al.* 2014), we applied the following additional filters to the dataset, following best practices in using eBird data laid out by Johnston *et al.* (2020). We used (i) only complete checklists; (ii) checklists travelling distance less than 10 kilometres and (iii) checklists with a survey duration between 10 and 300 min. This helps to limit the likelihood that unusual records were included in the analysis. To further robustness of our results, species with less than 500 observations in the firegrounds (i.e. presences) were excluded from the analysis to remove any potentially untrustworthy or unusual species data. Nine species from five waterbird families (*Anatidae, Ardeidae, Laridae, Pelecanidae, Phalacrocoracidae*) were also excluded from analysis to remove species which may not be using the terrestrial ecosystems.

Matching bird occurrence to fire data

To determine if a checklist was fire affected, we used the national extent of the 2019–2020 bushfires through the Department of Agriculture, Water and the Environment (DAWE 2020). To estimate the date of arrival of the fire front and assign each checklist as either before or after the fire, we used satellite data from Digital Earth Australia (DEA) Hotspots (Geoscience Australia 2020, see also Rowley *et al.* 2020). The fire arrival date varied between 27 October 2019 and 1 February 2020 for the sampling locations in this study. The DEA hotspot detection effort seeks to discover new spatial-temporal hotspots as quickly as possible and as such it provides a record of when the fire front was first detected to have arrived in different locations. Gaps in the orbital paths of the satellites means that this may be off by 12–24 h, but given the paucity of citizen science data at these precise places and times (due to the impeding or actively burning fire), the potential for misassigned checklists due to gaps in the orbital paths of satellites is low.

We used the Fire Extent and Severity Mapping data (FESM) provided by the Department of Planning, Industries and Environment (DPIE 2020b) to assign bird occurrence data with fire severity information. The FESM raster included fine scale information about the severity of each fire throughout the 2019–2020 bushfire season and was used to assign each checklist a severity value based on the pixel each checklist coordinate was located in. The median severity for each species included in the study was then calculated using all post-fire checklists that the species occurs on.

Trait data

Trait data for feeding guild, habitats, body size and sedentism were obtained from Garnett *et al.* (2015). Average body mass was preserved to be used as a measure for body size. We identified sedentary species by virtue of being exclusively locally dispersing, as opposed to species that move or migrate seasonally or sporadically. We quantified diet and habitat specialism by summing the total number of feeding guilds or habitat types each species is

doi:10.1111/aec.13105

associated with. Species with more generalist diets or habitat preferences therefore received a higher value than species with a more restricted diet or habitat. Data on the range sizes of birds were taken from Birdlife International (2021) using the value of full extent of occurrence for each species.

Statistical analysis

All analyses for this project were undertaken using the statistical computing software R (v4.0.2) in the integrated development environment RStudio. We relied heavily on the tidyverse for data manipulation and visualisation (Wickham *et al.* 2019). We converted the cleaned checklist data and fire extent shapefile to simple features for spatial analysis in R (Pebesma 2018). After combining these datasets, we removed all checklists that did not fall within the extent of the 2019–2020 mega-fires and all checklists above 25° South from the study.

For our final set of species ($N = 76$), we estimated the effect of the fire (i.e. categorical before *vs.* after) on the probability of a species being observed in a checklist, while also accounting for important covariates. To do this, we used generalised additive models (GAMs) – with a binomial error term – to model the change in probability of occurrence before and after the fires, for each species respectively. GAMs are an extension of Generalized Linear Models (GLMs), but the predictors can include parametric terms (i.e. as in GLMs) as well as a set of smooth functions that can be used to model unknown non-linear relationships with multiple predictors (Wood *et al.* 2016). For each model, the response variable was presence/absence of each species, and the predictor variable was before/after the fire. To account for differences in observer effort, seasonal effects, and biases in location effort, smooth functions were included in the creation of the models in order to adjust for the non-linear relationships of seasonality (month), sampling effort (duration and distance), and location, whereby the modelled response of our parametric term (i.e. before *vs.* after fire) considers these relationships that are not of inherent interest in our analysis. We used thin plate regression splines for the duration, distance and latitude/longitude smooth terms, and a cyclic cubic regression spline with 11 knots for seasonality (Wood 2003, 2004). We extracted the parameter estimate for each species' model and this parameter estimate represented the magnitude of change in the probability of occurrence after the fire.

To assess whether species' responses to fire were moderated by functional traits, we used five separate linear models with each of the five traits (i.e. feeding specialism, habitat specialism, body size, range size and sedentism) as the predictor variable and species fire responses, generated from the GAMs as the response variable. The uncertainty in the GAM coefficient estimate was used for inverse-variance weighting in these models. Bird body mass was logarithmically transformed in order to satisfy assumptions of linear regression. We produced a final linear model comparing each species' modelled fire response with the median severity in post-fire observations to test if the severity of fire would predict species' responses.

RESULTS

We included a total of 163 685 species observations originating from 8910 eBird checklists in our analysis (Fig. 1). Across the 76 species included in our analysis, the average number of observations for each species was 1636 ± 126, ranging from Grey Fantail with 4907 observations to Variegated Fairywren with 502 observations.

Of the 76 species included in the study, we found that 26 species showed a positive response, 23 showed a negative response and 27 showed no significant response (Fig. 2). Species with the highest estimated increases after fire included Crested Pigeon (*Ocyphaps lophotes*) and Sulphur-crested Cockatoo (*Cacatua galerita*), whereas the largest decrease in occurrence was in Fan-tailed Cuckoo (*Cacomantis flabelliformis*) and Olive-backed Oriole (*Oriolus sagittatus*).

We found a significant relationship between species' modelled fire responses and diet specialism ($P = 0.011$) explaining over 8% of variation ($R^2 = 0.085$; Fig. 3a). This indicates that a higher number of feeding guilds (i.e. generalist species) was associated with improved post-fire recolonisation. Similarly, specialist species with a narrower diet were more likely to have decreased after fire. Significance was also detected between a species' modelled fire response and body size ($P < 0.001$; $R^2 = 0.189$; Fig. 3b). This relationship suggests that smaller birds were associated with reduced occurrence after fire and larger birds increased occurrence. The model comparing fire response and range size was also significant ($P = 0.002$; $R^2 = 0.12$; Fig. 3c), with the model indicating that bird species with larger range sizes were more likely to have increased with fire and species with smaller ranges having decreased. Conversely, the model run on habitat specialism did not indicate a significant relationship with species fire responses ($P = 0.134$; $R^2 = 0.03$; Fig. 3d). The correlation between fire response and sedentism was also non-significant ($P = 0.3$; $R^2 = 0.014$; Fig. 3e). The final linear model comparing species' median fire severity and fire response did not detect a significant relationship ($P = 0.141$; $R^2 = 0.029$; Fig. 4).

DISCUSSION

We identified 23 species that were observed significantly less after the 2019–2020 summer mega-fires compared to before. The extent to which this reduction persists will be very important for the conservation status of these species, especially with a predicted increase in severity and frequency of such mega-fires (Pitman *et al.* 2007; Clarke & Evans 2019; van Oldenborgh *et al.* 2020). There are two

doi:10.1111/aec.13105

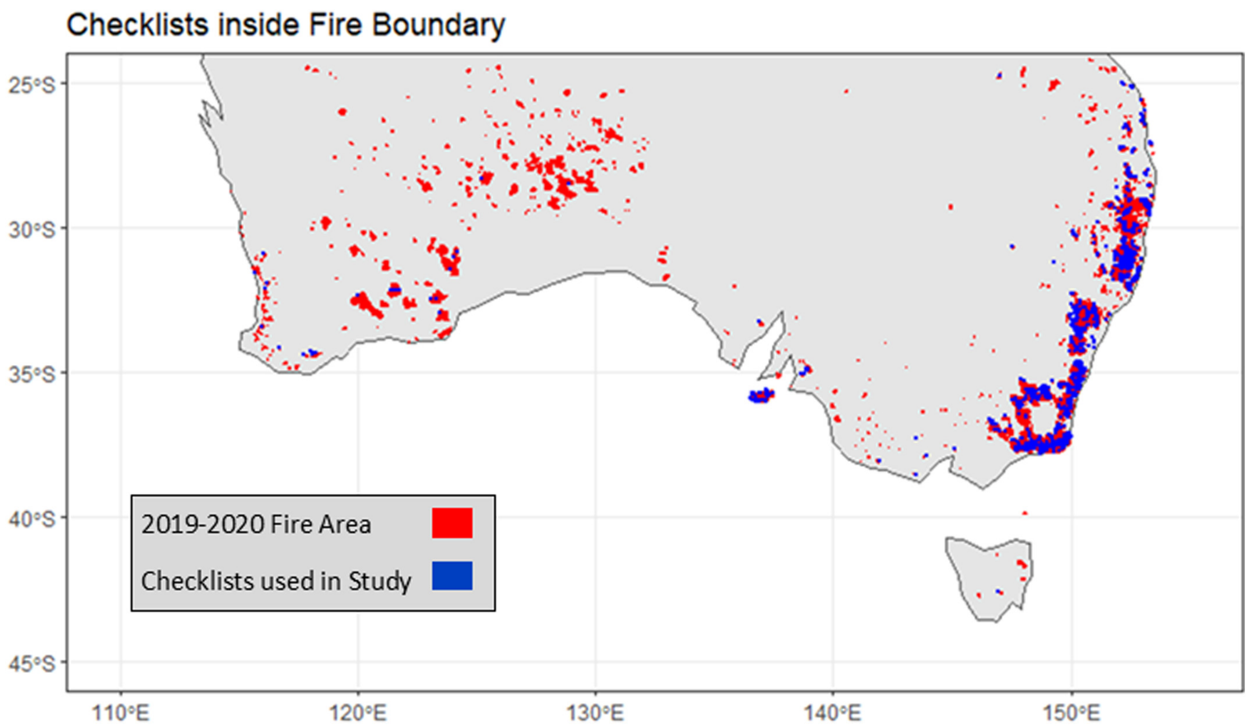

Fig. 1. Map of burnt area over the Australian 2019–2020 summer fire event (red) and eBird checklists inside fire boundary below 25° South (blue). [Colour figure can be viewed at wileyonlinelibrary.com]

alternative hypotheses that could help explain our results. First, individuals of these species could have moved to unburnt parts of the region and will return to the firegrounds once the vegetation has regrown sufficiently. Second, the fires led, directly or indirectly, to higher than typical mortality in these species. In contrast, 26 species were observed significantly more after the fire event, highlighting that there are some 'winners' as well as 'losers' in response to fires. This is likely due to new resources that are created in the wake of fire (Pausas & Parr 2018) but may also be due to increased detectability of birds in the post-fire environment (Hutto 2016; Einoder *et al.* 2018). Identifying general patterns in species responses to fire will help differentiate which species are predicted to be able to adapt to future fire events more readily.

Our results confirm our hypothesis that species with a more specialised diet may be less effective at post-fire recolonisation. Highly specialised animals may be common under stable environmental conditions, however become vulnerable to rapid decline when there is environmental change (Lindenmayer *et al.* 2011). In the event of fire, drastic and lasting changes occur to food resources which favour species that can take advantage of this change while disadvantaging other species (Banks *et al.* 2011; Pausas & Parr 2018).

We also found that smaller birds were more likely to have decreased after fire. Small birds are generally more reliant on a denser, more developed vegetation structure for cover (Rodríguez *et al.* 2001; LaManna *et al.* 2015) to mitigate higher predation rates than larger birds (Götmark & Post 1996). In most cases, dense understorey vegetation important for birds is drastically reduced in fire events (Wooller & Calver 1988; Rodríguez *et al.* 2001; Gill 2012; Swan *et al.* 2015). Reduction of biomass from fire also reduces food availability which has been observed to increase risk taking in an already predation prone environment (Turcotte & Desrochers 2003; Leahy *et al.* 2016).

The final trait that we identified as important for a species' post-fire recolonisation was range size. Larger range sizes are associated with larger populations since larger geographic areas can support greater numbers of birds (Harris & Pimm 2007). This means that in the event of a large-scale disturbance event like the 2019–2020 mega-fires, birds that are more abundant and widespread have a greater ability to disperse and recolonise burnt areas as they are more likely to occupy unburnt refuge areas (Gaston 2003; Birand *et al.* 2012). Our results failed to confirm our hypotheses that sedentism or habitat specialism was important for species recolonisation after fire. This result may be due to a general adaptability of much

doi:10.1111/aec.13105

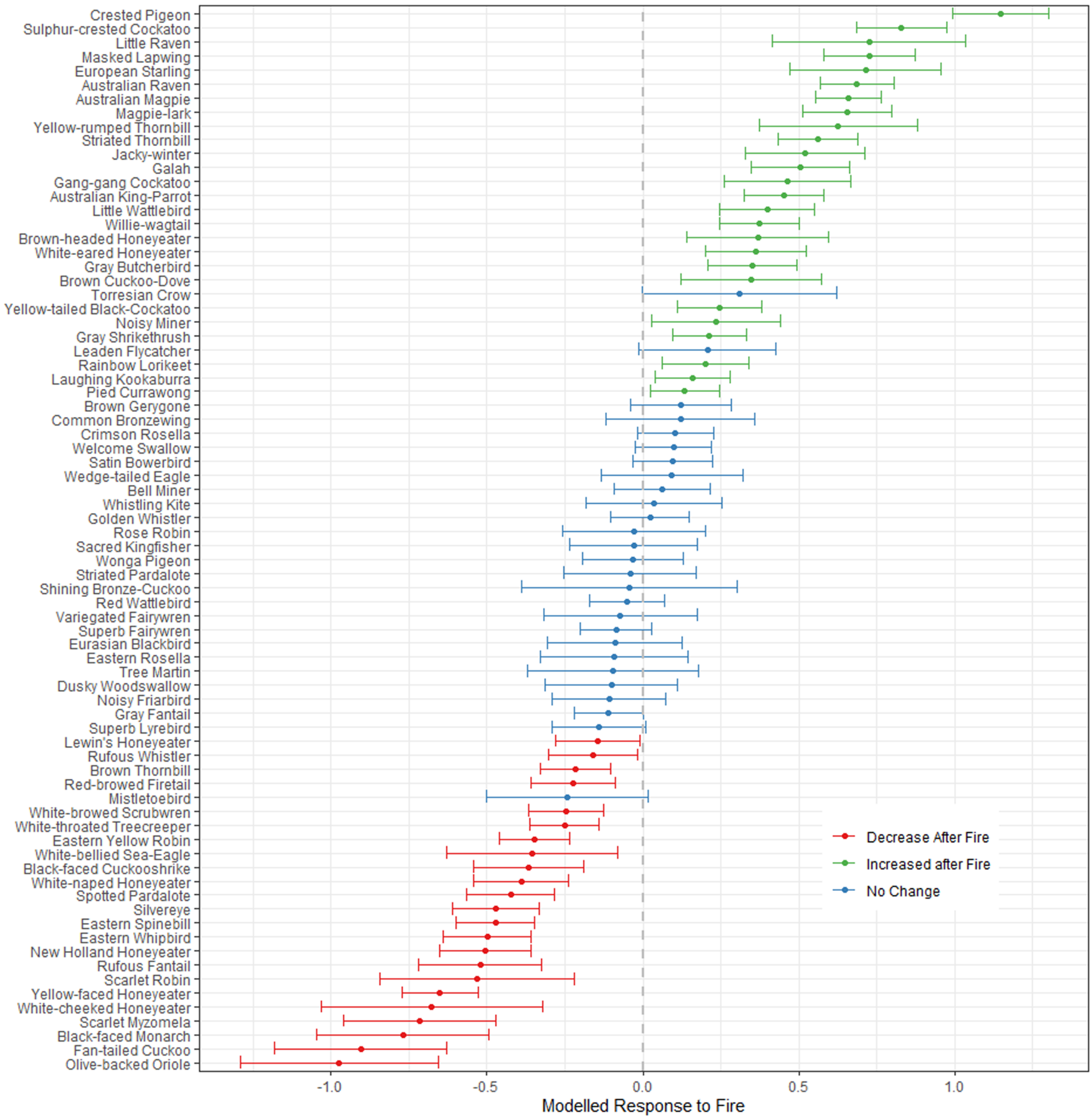

Fig. 2. Responses to fire as calculated by generalised additive models for each species. Species are ranked by coefficient estimate (±SE), where a larger positive value represents a greater increase in probability of occurrence after fire and smaller negative value represents a greater reduction in probability of occurrence after fire. Decrease after fire (red); Increased after fire (green); No change (blue). [Colour figure can be viewed at wileyonlinelibrary.com]

of the Australian fauna to fire (Woinarski 1990; Nimmo *et al.* 2019; Ward *et al.* 2020).

Identifying species' post-fire occurrences can be an indicator of successional processes that result from the resource redistribution of fire disturbances, and thus further contribute to an understanding of how fire can benefit some species while disadvantaging others. The species with the highest estimated increase in probability of occurrence after the fire event was the Crested Pigeon (*Ochyphaps lophotes*). This species was most likely able to profit from the extensive fires due to increases in their main food sources, low dependence on dense vegetation structure and dispersal from elsewhere in its extensive range. Crested Pigeons eat seeds and herbaceous material from grasses and forbs (Mulhall & Lill 2011). These resources have been shown to increase significantly in fire disturbed environments since

doi:10.1111/aec.13105

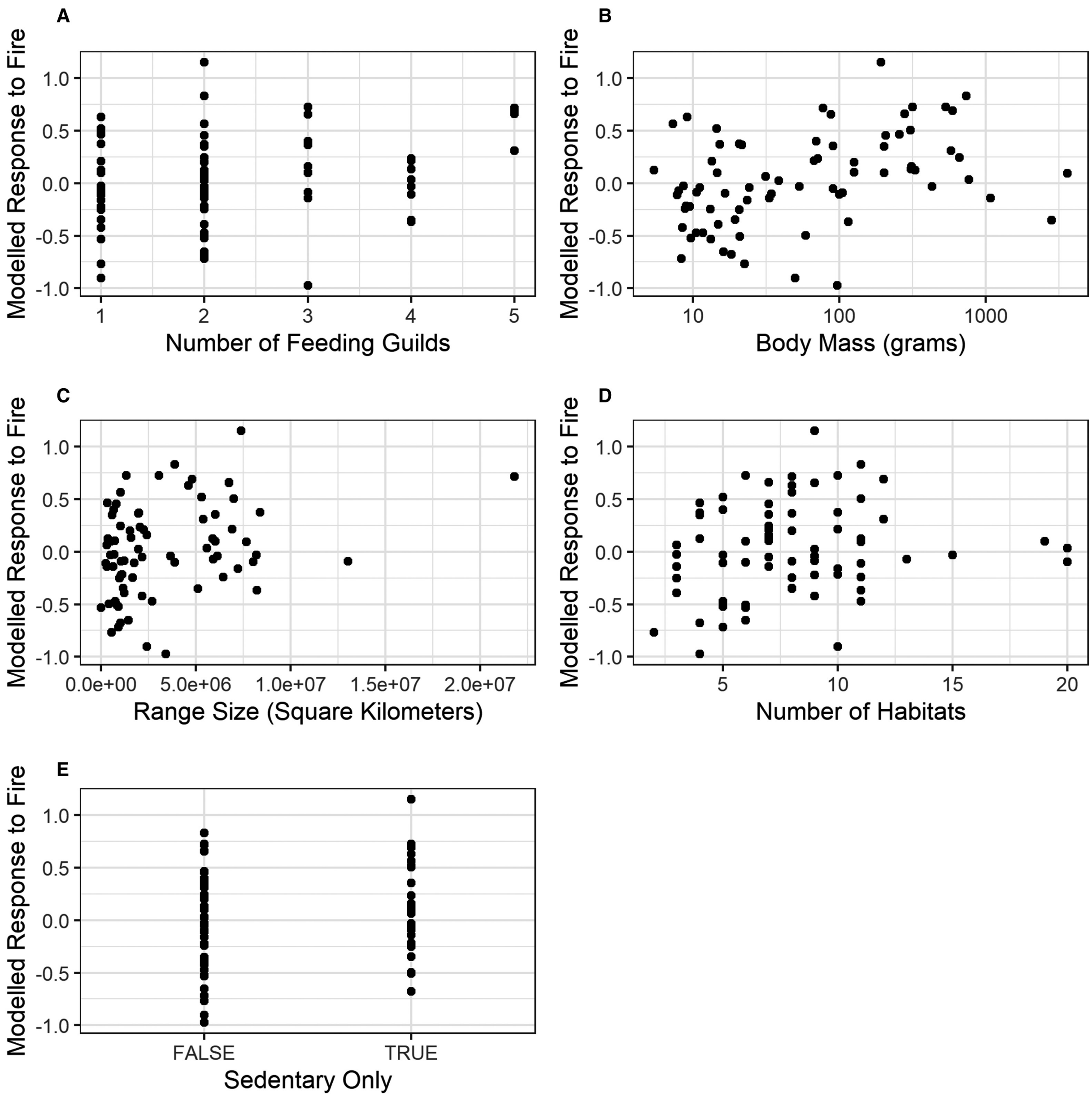

Fig. 3. Plot of modelled fire response against degree of diet specialism (a), average body mass (log-transformed) (b), range size (c), degree of habitat specialism (d) and sedentism (e), for each bird species.

ephemeral herbs and grasses are rapid post-fire colonisers (Bell *et al.* 1993; Romme *et al.* 2011) and seeds are dropped *en masse* by many woody plants following fire events (Specht 1981; Andersen 1988). Crested Pigeons' efficacy in utilising these resources and their preference for open environments also contributes to their success in highly disturbed urban areas (Mulhall & Lill 2011). Furthermore, populations refuging in urban areas may have been important source populations for recolonisation into the fire grounds.

In contrast, many birds that decreased in occurrence after fire, such as the Black-faced Monarch (*Monarcha melanopsis*), were specialised on terrestrial invertebrates. This may be due to invertebrate populations remaining low in the first 4 months after fire since foliage is still in early stages of regeneration and insect grazing likely occurs at higher rates in mature forests (Springett 1978). Due to the small body size of this species relative to others used in this analysis and their dependence on midstories for foraging (Pratt & Beehler 2015), Black-faced Monarchs were

doi:10.1111/aec.13105

likely more vulnerable to the effects of fire on predation rates and foraging behaviour. Species with diets specialised on food that takes longer to recover from a fire event, small or predator prone species and species with diminished dispersal ability may be more deserving of management attention.

The massive firegrounds of the 2019–2020 fires dwarfed all possible attempts at data collection by professional scientists in the immediate aftermaths. However, citizen scientists were able to collect data at scale in the aftermath (Callaghan & Gawlik 2015; Kirchhoff *et al.* 2020). That said, there are some limitations to consider when using such a data source. The fire itself was very patchy, with both unburnt patches inside the firegrounds and variation in fire severity on the scale of meters. The nature of eBird data does not allow us to examine the nature of the patches that different species were using or how they were using them, for example, foraging for food or resting (Sullivan *et al.* 2009, 2014; Callaghan & Gawlik 2015; Johnston *et al.* 2020). We also acknowledge some sampling biases in the data including eBird checklists being more numerous in coastal and more densely populated areas (Fig. 1) and the limited number of usable checklists in the four months after fire compared with the number of checklists used before the fire event. A major limitation in the use of citizen science data is not being able to control where and when sampling effort is exerted, for example: in this study, the sampling effort for post-fire observations may have been greatly reduced due to Coronavirus restrictions. However, with citizen science participation growing rapidly (Lee *et al.* 2020), the ability for scientists to account for these biases is improving. As an example, with a longer time series of data post fire, our work can be extended to test other hypotheses such as how birds recolonise areas temporally as opposed to the binary before/after we tested here. Or, with more spatially-refined data, the distance from the fire edge could be an important variable that explains species-specific or bird community level responses

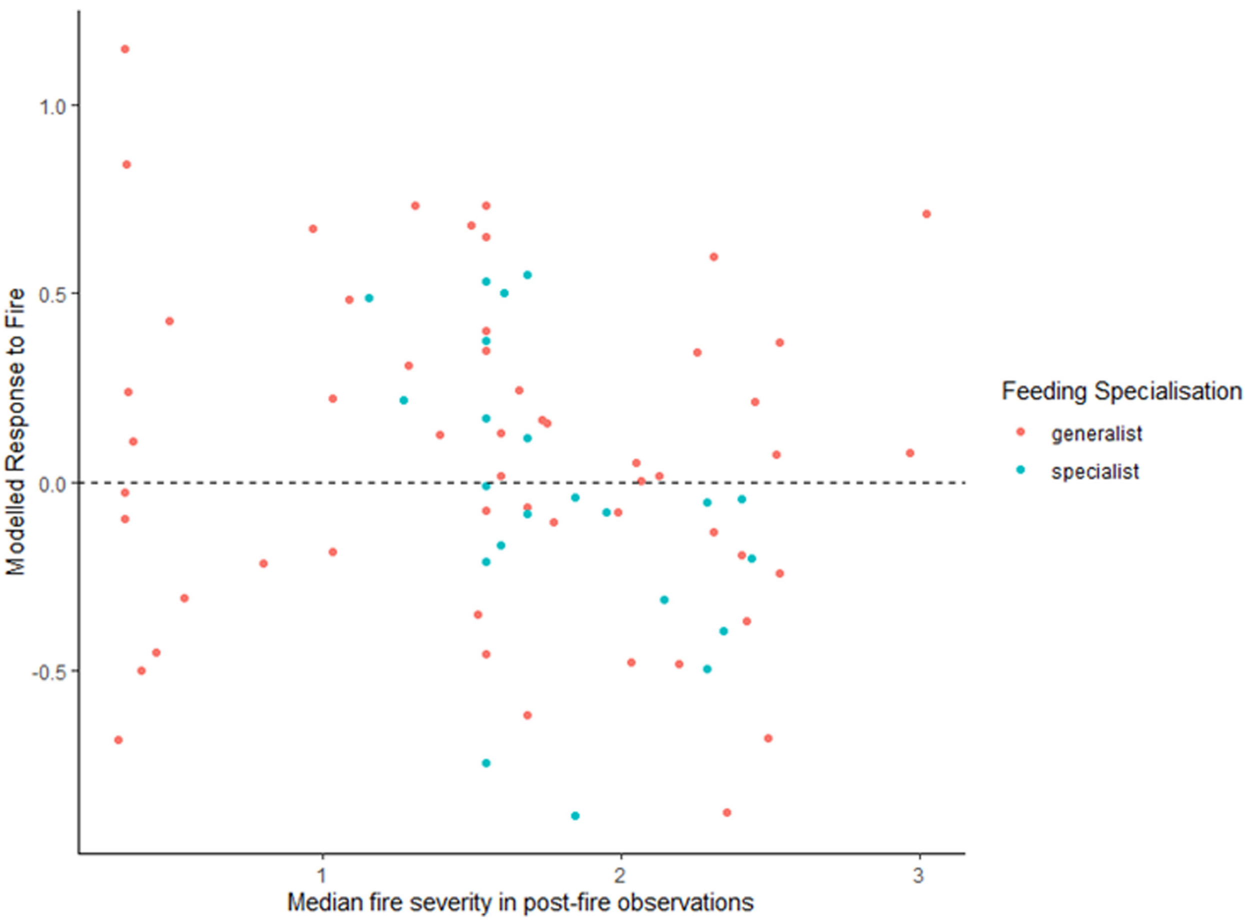

Fig. 4. Scatterplot of modelled fire response against median fire severity grouped by feeding habit, where generalists are species belonging to more than one feeding guild. Interactive version at: https://josh-lee1.github.io/eBird-Fire-Index/interactive_figure.html. Generalists (red); Specialists (blue). [Colour figure can be viewed at wileyonlinelibrary.com]

 doi:10.1111/aec.13105

and can serve as the basis for future research. Therefore, while citizen science data such as eBird are clearly valuable to inform macroecological patterns, on-the-ground data should be integrated with these findings in the future to better inform our understanding of the impacts of bushfires on bird diversity and usage in post-fire environments.

Immediate post-fire observations, available through citizen science, provided important information into the long-term effects of the massive 2019–2020 fires. The decline of 23 species identified in this study and the extent to which this decline persists through time will be an important concern for the conservation status of these species. The unprecedented scale of the mega-fires produced an enormous amount of public attention on conservation problems and objectives, as well as an unprecedented strain on the biota of Australia's forest ecosystems. Fire events are expected to become more severe and frequent under the influence of anthropogenic climate change, exacerbating the need for efficient and effective conservation policies and management (Clarke & Evans 2019; van Oldenborgh *et al.* 2020). To effectively address the conservation concerns raised by this unprecedented bushfire season and fire events to come, it is important for efforts to be targeted at species with the greatest need, and citizen science will likely play a key role in this effort.

ACKNOWLEDGEMENTS

We thank the 12 800 Australian eBirders who have provided the data that have made this project possible.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

Joshua Sean Lee: Conceptualization (lead); Data curation (lead); Formal analysis (equal); Methodology (equal); Project administration (equal); Software (equal); Writing-original draft (lead); Writing-review & editing (equal). **Corey Callaghan:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Software (equal); Supervision (equal); Writing-review & editing (equal). **Will Cornwell:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Software (equal); Supervision (equal); Writing-review & editing (equal).

REFERENCES

Ainsworth G. B., Fitzsimons J. A., Weston M. A. & Garnett S. T. (2018) The culture of bird conservation: Australian stakeholder values regarding iconic, flagship and rare birds. *Biodivers. Conserv.* **27,** 345–63.

Albanesi S., Dardanelli S. & Bellis L. M. (2014) Effects of fire disturbance on bird communities and species of mountain Serrano forest in central Argentina. *J. Forest Res.* **19,** 105–14.

Andersen A. N. (1988) Immediate and longer-term effects of fire on seed predation by ants in sclerophyllous vegetation in south-eastern Australia. *Aust. J. Ecol.* **13,** 285–93.

Banks S. C., Knight E. J., McBurney L., Blair D. & Lindenmayer D. B. (2011) The effects of wildfire on mortality and resources for an arboreal marsupial: resilience to fire events but susceptibility to fire regime change. *PLoS One* **6,** e22952.

Bell D. T., Plummer J. A. & Taylor S. K. (1993) Seed germination ecology in southwestern Western Australia. *Bot. Rev.* **59,** 24–73.

Birand A., Vose A. & Gavrilets S. (2012) Patterns of species ranges, speciation, and extinction. *Am. Nat.* **179,** 1–21.

Bird T. J., Bates A. E., Lefcheck J. S. *et al.* (2014) Statistical solutions for error and bias in global citizen science datasets. *Biol. Cons.* **173,** 144–54.

BirdLife International. (2021) IUCN Red List for birds. [Online]. Available from: http://www.birdlife.org [Accessed March 24, 2021].

Boer M. M., Resco de Dios V. & Bradstock R. A. (2020) Unprecedented burn area of Australian mega forest fires. *Nat. Clim. Chang.* **10,** 170.

Bradstock R. A., Williams J. E. & Gill M. A. (2002) *Flammable Australia: The Fire Regimes and Biodiversity of a Continent.* Cambridge University Press, Cambridge.

Callaghan C. T. & Gawlik D. E. (2015) Efficacy of eBird data as an aid in conservation planning and monitoring. *J. Field Ornithol.* **86,** 298–304.

Cary G., Bradstock R., Gill A. & Williams R. (2012) Global change and fire regimes in Australia. In *Flammable Australia: Fire regimes, Biodiversity and Ecosystems in a Changing World*, pp. 149–69. [online]. Available from: https://books.google.fr/books?hl=fr&lr=&id=PCNsEdwRfSsC&oi=fnd&pg=PA149&dq=Global+change+and+fire+regimes+in+Australia&ots=p54__vHQqm&sig=eFE95ZVomJqt9VWfhTIjVjfFALw

Cavallero L., Raffaele E. & Aizen M. A. (2013) Birds as mediators of passive restoration during early post-fire recovery. *Biol. Conserv.* **158,** 342–50.

Clarke H. & Evans J. P. (2019) Exploring the future change space for fire weather in southeast Australia. *Theor. Appl. Climatol.* **136,** 513–27.

Davies T., Cowley A., Bennie J. *et al.* (2019) Correction: Popular interest in vertebrates does not reflect extinction risk and is associated with bias in conservation investment. *PLoS One* **14,** 1–13.

Department of Agriculture, Water and the Environment (DAWE) (2020) National Indicative Aggregated Fire Extent Datasets. [online] [cited 23 June 2020.] Available from URL: https://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B9ACDCB09-0364-4FE8-9459-2A56C792C743%7D

Department of Planning, Industry and Environment (DPIE) (2020a) NSW Fire and the Environment 2019-20 Summary. [online] [cited 1 October 2020.] Available from

URL: https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Parks-reserves-and-protected-areas/Fire/fire-and-the-environment-2019-20-summary-200108.pdf

Department of Planning, Industry and Environment (DPIE) (2020b) Fire Extent and Severity Mapping. [online] [cited 23 September 2020.] Available from URL: https://data.gov.au/dataset/ds-nsw-c28a6aa8-a7ce-4181-8ed1-fd221dfcefc8/details?q=

Eglington S. M., Noble D. G. & Fuller R. J. (2012) A meta-analysis of spatial relationships in species richness across taxa: birds as indicators of wider biodiversity in temperate regions. *J. Nat. Conserv.* **20,** 301–9.

Einoder L. D., Southwell D. M., Lahoz-Monfort J. J. *et al.* (2018) Occupancy and detectability modelling of vertebrates in northern Australia using multiple sampling methods. *PLoS One* **13,** e0203304.

Filkov A. I., Ngo T., Matthews S., Telfer S. & Penman T. D. (2020) Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *J. Saf. Sci. Resilience* **1,** 44–56.

Garnett S. T., Duursma D. E., Ehmke G. *et al.* (2015) Biological, ecological, conservation and legal information for all species and subspecies of Australian bird. *Sci. Data* **2,** 1–6. https://doi.org/10.1038/sdata.2015.61

Gaston K. J. (2003) *The Structure and Dynamics of Geographic Ranges*. Oxford University Press, Oxford.

Geoscience Australia (2020) Digital Earth Australia Hotspots - Public Data. Digital Earth Australia Hotspots. [online]. Available from: https://hotspots.dea.ga.gov.au/files [Accessed September 23, 2020].

Gill A. M. (2012) *Bushfires and biodiversity in southern Australian forests* pp. 235–52. CSIRO Publishing, Melbourne.

Gill M. A. (1996) How fires affect biodiversity. In: *Fire and Biodiversity: The Effects and Effectiveness of Fire Management-Proceedings of the conference held 8-9 October 1994*. Department of the Environment, Sport and Territories, Melbourne.

Götmark F. & Post P. (1996) Prey selection by sparrowhawks, *Accipiter nisus*: relative predation risk for breeding passerine birds in relation to their size, ecology and behaviour. *Phil. Trans. Roy. Soc. Ser. B Biol. Sci.* **351,** 1559–77.

Gregory R., Noble D., Field R., Marchant J., Raven M. & Gibbons D. (2003) Using birds as indicators of biodiversity. *Ornis Hung.* **12,** 11–24.

Gregory R. D. & van Strien A. (2010) Wild bird indicators: Using composite population trends of birds as measures of environmental health. *Ornithol. Sci.* **9,** 3–22.

Harris G. & Pimm S. (2007) Range size and extinction risk in forest birds. *Conserv. Biol.* **22,** 163–71.

Hutto R. L. (2016) Should scientists be required to use a model-based solution to adjust for possible distance-based detectability bias? *Ecol. Appl.* **26,** 1287–94.

Johnston A., Hochachka W. & Strimas-Mackey M. *et al.* (2020) Analytical guidelines to increase the value of citizen science data: using eBird data to estimate species occurrence. *bioRxiv*. https://doi.org/10.1101/574392. [online]. Available from: https://cornelllabofornithology.github.io/ebird-best-practices/

Kirchhoff C., Callaghan C. T., Keith D. A. *et al.* (2020) Rapidly mapping fire effects on biodiversity at a large-scale using citizen science. *Sci. Total Environ.* **755,** 142348.

LaManna J. A., Hemenway A. B., Boccadori V. & Martin T. E. (2015) Bird species turnover is related to changing predation risk along a vegetation gradient. *Ecology* **96,** 1670–80.

Leahy L., Legge S. M., Tuft K. *et al.* (2016) Amplified predation after fire suppresses rodent populations in Australia's tropical savannas. *Wildl. Res.* **42,** 705–16.

Lee K. A., Lee J. R. & Bell P. (2020) A review of Citizen Science within the Earth Sciences: potential benefits and obstacles. *Proc. Geol. Assoc.* **131,** 605–17.

Lindenmayer D. B., Wood J. T., McBurney L., MacGregor C., Youngentob K. & Banks S. C. (2011) How to make a common species rare: a case against conservation complacency. *Biol. Conserv.* **144,** 1663–72.

Loyn R. H. (1997a) Effects of an extensive wildfire on birds in far eastern Victoria. *Pac. Conserv. Biol.* **3,** 221–34.

Loyn R. H. (1997b) Effects of an extensive wildfire on birds in far eastern Victoria. *Pac. Conserv. Biol.* **3,** 221–34.

McKinley D. C., Miller-Rushing A. J., Ballard H. L. *et al.* (2017) Citizen science can improve conservation science, natural resource management, and environmental protection. *Biol. Conserv.* **208,** 15–28.

Mulhall S. & Lill A. (2011) What facilitates urban colonisation by Crested Pigeons *Ochyphaps lophotes*? *Corella* **35,** 73–81.

Nimmo D. G., Avitabile S., Banks S. C. *et al.* (2019) Animal movements in fire-prone landscapes. *Biol. Rev.* **94,** 981–98.

Nolan R. H., Boer M. M., Collins L. *et al.* (2020) Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Glob. Change Biol.* **26,** 1039–41.

Pausas J. G. & Parr C. L. (2018) Towards an understanding of the evolutionary role of fire in animals. *Evol. Ecol.* **32,** 113–25.

Pebesma E. (2018) Simple features for R: standardized support for spatial vector data. *R J.* **10,** 439–46.

Pitman A. J., Narisma G. T. & McAneney J. (2007) The impact of climate change on the risk of forest and grassland fires in Australia. *Clim. Change.* **84,** 383–401.

Pons P. & Prodon R. (1996) Short term temporal patterns in a Mediterranean shrubland bird community after wildfire. *Acta Oecol.* **17,** 29–41.

Pratt T. K. & Beehler B. M. (2015) Monarchs: Monarchidae. *Birds of New Guinea* pp. 460–6. Princeton University Press, Princeton.

Prowse T. A. A., Collard S. J. & Blackwood A. *et al.* (2017) Prescribed burning impacts avian diversity and disadvantages woodland-specialist birds unless long-unburnt habitat is retained. *Biol. Conserv.* **215,** 268–76.

Purdie R. W. & Slatyer R. O. (1976) Vegetation succession after fire in sclerophyll woodland communities in south-eastern Australia. *Aust. J. Ecol.* **1,** 223–36.

Robinson N. M., Leonard S. W. J., Bennett A. F. & Clarke M. F. (2014) Refuges for birds in fire-prone landscapes: The influence of fire severity and fire history on the distribution of forest birds. *For. Ecol. Manage.* **318,** 110–21.

Rodríguez A., Andrén H. & Jansson G. (2001) Habitat-mediated predation risk and decision making of small birds at forest edges. *Oikos* **95,** 383–96.

Romme W. H., Boyce M. S., Gresswell R. *et al.* (2011) Twenty years after the 1988 Yellowstone fires: lessons about disturbance and ecosystems. *Ecosystems* **14,** 1196–215.

Rowley J. J., Callaghan C. T. & Cornwell W. K. (2020) Widespread short-term persistence of frog species after the 2019–2020 bushfires in eastern Australia revealed by citizen science. *Conserv. Sci. Pract.* **2,** e287.

Specht R. (1981) Heathlands. In: *Australian Vegetation*, 4th edn (ed R. Groves) pp. 253–75. Cambridge University Press, Cambridge.

Springett B. P. (1978) On the ecological role of insects in Australian eucalypt forests. *Aust. J. Ecol.* **3,** 129–39.

 doi:10.1111/aec.13105

Sullivan B. L., Aycrigg J. L., Barry J. H. *et al*. (2014) The eBird enterprise: an integrated approach to development and application of citizen science. *Biol. Cons.* **169,** 31–40.

Sullivan B. L., Wood C. L., Iliff M. J., Bonney R. E., Fink D. & Kelling S. (2009) eBird: A citizen-based bird observation network in the biological sciences. *Biol. Conserv.* **142,** 2282–92.

Swan M., Christie F., Sitters H., York A. & Di Stefano J. (2015) Predicting faunal fire responses in heterogeneous landscapes: the role of habitat structure. *Ecol. Appl.* **25,** 2293–305.

Turcotte Y. & Desrochers A. (2003) Landscape-dependent response to predation risk by forest birds. *Oikos* **100,** 614–8.

Turner M. G., Baker W. L., Peterson C. J. & Peet R. K. (1998) Factors influencing succession: lessons from large, infrequent natural disturbances. *Ecosystems* **1,** 511–23.

van Eeden L., Nimmo D. & Mahony M. *et al.* (2020) Australia's 2019-2020 Bushfires: The Wildlife Toll - Interim Report. [online] [cited 1 October 2020.] Available from URL: https://www.wwf.org.au/what-we-do/bushfire-recovery/in-depth/resources/australia-s-2019-2020-bushfires-the-wildlife-toll#gs.9t5imf

van Oldenborgh G. J., Krikken F., Lewis S. *et al.* (2020) Attribution of the Australian bushfire risk to anthropogenic climate change. *Nat. Hazard. Earth Syst. Sci.* **21,** 941–60.

Ward M., Tulloch A. I. T., Radford J. Q. *et al.* (2020) Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nat. Ecol. Evol.* **4,** 1321–6.

Whelan R. J., Rodgerson L. O., Dickman C. & Sutherland E. F. (2002) Critical life cycles of plants and animals: developing a process-based understanding of population changes in fire-prone landscapes. In: *Flammable Australia: the fire regimes and biodiversity of a continent* (eds R. A. Bradstock, J. Williams & A. M. Gill) pp. 94–124. Cambridge University Press, Cambridge.

Wickham H., Averick M., Bryan J. *et al.* (2019) Welcome to the Tidyverse. *J. Open Source Softw.* **4,** 1686.

Woinarski J. C. Z. (1990) Effects of fire on the bird communities of tropical woodlands and open forests in northern Australia. *Aust. J. Ecol.* **15,** 1–22.

Wood C., Sullivan B., Iliff M., Fink D. & Kelling S. (2011) eBird: engaging birders in science and conservation. *PLoS Biol.* **9,** e1001220.

Wood S. N. (2003) Thin plate regression splines. *J. R. Stat. Soc. Series B Stat. Methodol.* **65,** 95–114.

Wood S. N. (2004) Stable and efficient multiple smoothing parameter estimation for generalized additive models. *J. Am. Stat. Assoc.* **99,** 673–86.

Wood S. N., Pya N. & Säfken B. (2016) Smoothing parameter and model selection for general smooth models. *J. Am. Stat. Assoc.* **111,** 1548–63.

Wooller R. D. & Calver M. C. (1988) Changes in an assemblage of small birds in the understorey of dry sclerophyll forest in southwestern Australia after fire. *Wildl. Res.* **15,** 331–8.

doi:10.1111/aec.13105