Using citizen science to measure recolonisation of birds after the Australian 2019-20 mega-fires

Joshua S Lee[a*], Corey T Callaghan[ab], William K Cornwell[ab]

a Centre for Ecosystem Science; School of Biological, Earth and Environmental Sciences; UNSW Sydney, Sydney, NSW 2052, Australia

b Ecology & Evolution Research Centre; School of Biological, Earth and Environmental Sciences; UNSW Sydney, Sydney, NSW 2052, Australia

*Corresponding author:
Joshua S. Lee
Centre for Ecosystem Science
School of Biological, Earth and Environmental Sciences,
UNSW Sydney
Email: Joshua.s.lee@unsw.edu.au
Phone: +61 432 401 194

Note: This is a pre-print and has not undergone full peer-review.

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 2019-20 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, and the specialisation of diet and habitat. Using generalised additive models, we modelled the response of 76 bird species in SE Australia to the 2019-20 mega-fires. Twenty-two species decreased in occurrence after the fire; thirty species increased; and no significant effect was found for the remaining twenty-four species. Furthermore, diet specialism was associated with reduced recolonisation after fire, with diet specialists less likely to be found in burned 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.

Keywords

"bird traits", "bushfire", "citizen science", "eBird", "post-fire recovery".

Introduction

The 2019-20 Australian bushfire season was one of the largest and longest on record (Nolan *et al.* 2020; Filkov *et al.* 2020). Almost 19 million hectares were directly affected by the fire including the burning of 5.8 million hectares of temperate broadleaf forest (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 2019-20 mega-fires (Eeden *et al.* 2020) potentially driving threatened species closer to extinction (DPIE 2020a). In the wake of these immense disturbance events it is important to understand the process of ecosystem recovery to implement effective conservation actions. There is a large interest in bird conservation globally (Davies *et al.* 2019). Conservation efforts by both government and non-government organisations have been shown to favour bird species with higher social interest (Ainsworth *et al.* 2018), making birds an important group for procuring recovery funding, which may benefit the entirety of the ecosystems. Birds are also useful indicators of environmental health since bird populations and diversity may reflect the composition of food and habitat resources in an environment (Eglington *et al.* 2012; Gregory and Strien 2010; Gregory *et al.* 2003). 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; Pausas and Parr 2018; Cavallero *et al.* 2013). Therefore, 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 and associated mosaic of different ecosystems that were impacted means that a larger proportion of some 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 is beyond the capacity of university or government research groups to easily obtain. Moreover, data needs to be collected relatively quickly because many important post-fire processes occur soon after the event. One solution to this set of problems is mobilizing citizen scientists (Kirchhoff *et al.* 2020a). Citizen science is an increasingly popular tool for informing science and policy as more online services improve at storing and collating data. The major advantage of using citizen science data is that 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 phenomenon throughout the continent of Australia (Bradstock *et al.* 2002). The life histories of many plants and animals in various ecosystems have evolved to allow species to cope with fire (Purdie and Slatyer 1976; Cary *et al.* 2012). The post-fire environment, especially after severe fire, is generally thought to be devoid of many resources and habitat features (Loyn 1997a). However, the wasteland is not completely barren: new resources are created in the wake of fire events, making post-fire environments productive foraging grounds for some recolonising species (Pausas and Parr 2018; Albanesi *et al.* 2014; Loyn 1997b; Pons and Prodon 1996; Prowse *et al.* 2017). However, the heterogeneity of the burn and 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). Conversely, species with more flexible behaviours and diets may benefit from the redistribution of resources from a fire event (Pausas and Parr 2018). 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). Furthermore, in large-scale fire events where bird mortality and displacement are expected to be high, a species' dispersal ability may be important for recolonisation (Robinson *et al.* 2014; Turner *et al.* 1998; Whelan *et al.* 2002). It is important to understand how bird traits are associated with post-fire recovery in order to make predictions about the impacts of future fires across the world.

We had three main objectives: (1) to quantify the response of species occurrence as either increasing, decreasing, or no change in response to the fire; and (2) to model species' fire responses against four potentially important bird traits (i.e., sedentism, body size, and the specialisation of diet and habitat) for post-fire recolonisation; and (3) 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, 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. Species identified in this study to have decreased in occurrence in the months following the 2019-2020 mega-fire event may be worthy of increased conservation attention both in the coming months and in the aftermath of future fires.

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 close to 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 the 1st January 2010 and the 1st May 2020. In order to account for potential biases associated with citizen science data (Bird *et al.* 2014), and applied the following additional filters to the dataset by using (*sensu* Johnston et al. 2020): (1) only complete checklists; (2) checklists travelling distance less than 10 kilometres; and (3) checklists with a survey duration between 10 and 300 minutes.

Matching bird occurrence to fire data

To determine if a checklist was fire affected, we used the national extent of the 2019/20 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). This fire arrival date varied between the 27th October 2019 and the 1st February 2020 for the sampling locations in this study. Th 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 hours, 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 mis-assigned 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 2019-20 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. We produced a linear model comparing each species' modelled fire response with the median severity in post-fire observations.

Trait data

Trait data was 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 associated with. Species with more generalist diets or habitat preferences therefore received a higher value than species with a more restricted diet or habitat.

Statistical analysis

All analyses for this project was 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 visualization (Wickham *et al.* 2019). We converted the cleaned checklist data and fire extent shapefile to simple features for spatial analysis in R (Pebesma 2018). We then joined these features with a variable added for locating datapoints within the shapefile extent. We removed all checklists that did not fall within the extent of the 2019-20 mega-fires and all checklists above 25° South from the study.

Only species with a minimum of 500 observations in the firegrounds (i.e., presences) were considered for analyses. Nine species from five waterbird families (*Anatidae, Ardeidae, Laridae, Pelecanidae, Phalacrocoracidae*) were excluded from analysis to remove species which may not be using the terrestrial ecosystems. For our final set of species (N=76), we estimated the effect of the fire (i.e., before versus after) on the probability of the species being observed in a checklist, while also accounting for important covariates. We then compared the proportion of checklists each species was present on before and after the fire event. Species that preferentially use the post-fire environment should be on a greater proportion of checklists post-fire compared to pre-fire. Species whose use of those areas declined, following the fire event should be found on fewer. To do this, we used generalised additive models (GAMs) - with a binomial error term - to model the change in detection probability before and after the fires, for each species respectively. 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, smoothers were included in the creation of the models in order to adjust for seasonality (month), sampling effort (duration and distance), and location. We used thin plate regression splines for the duration, distance and latitude/longitude smooth terms, and a cyclic cubic regression spline with eleven knots for seasonality.

In order to assess whether the species' response to fire, generated from the GAMs, was moderated by species' traits, we used four separate linear models with each of the four traits (i.e., feeding specialism, habitat specialism, body size, and sedentism) as the predictor variable. The uncertainty in the GAM coefficient estimate was used for inverse-variance weighting in these models. Bird body size was log-transformed in order to satisfy assumptions of linear regression.

Results

We included a total of 163,685 species observations originating from 8,910 eBird checklists in our analysis (Figure 1). Across the 76 species included in our analysis the average number of observations for each species was 1,636 +/- 126, ranging from Grey Fantail with 4,907 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 (Figure 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 ($R^2= 0.085$) (Figure 3: A). 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.

Conversely, the model run on habitat specialism did not indicate a significant relationship with species fire responses ($p= 0.134$; $R^2= 0.030$; Figure 3: B). The correlation between fire response and sedentism was also non-significant ($p= 0.3$; $R^2= 0.014$; Figure 3: C). The final linear regression comparing fire response to body size also failed to detect a significant relationship ($p=0.248$; $R^2= 0.018$; Figure 3: D). The final linear model comparing species' median fire severity and fire response did not detect a significant relationship ($P=0.141$; $R^2= 0.029$).

Discussion

We identified 23 species that were observed significantly less after the 2019-20 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 (Clarke and Evans 2019; van Oldenborgh *et al.* 2020; Pitman *et al.* 2007). There are two alternate hypotheses that could help explain our results. First, individuals of these species could have moved to unburned 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 post-fire environment (Pausas and Parr 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 suggest 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 and Parr 2018). This finding confirms our hypothesis that bird species with a greater diet breadth would have improved post-fire recolonisation than species with specialist diets. This result may have important implications future fire events and disturbance ecology more generally. Our results failed to confirm our hypotheses that body size, sedentism or habitat specialism was important for species recolonisation after fire. This result may be due to a general adaptability of much of the Australian fauna to fire (Nimmo *et al.* 2019; Woinarski 1990; Ward *et al.* 2020).

Identifying species' post-fire occurrences can be an indicator of successional processes and 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 occurrence after the fire event was Crested Pigeons (*Ochyphaps lophotes*). This species was most likely able to profit from the extensive fires due to increases in their main food sources: Crested Pigeons eat seeds and herbaceous material from grasses and forbs (Mulhall and Lill 2011). These resources have been shown to increase significantly in fire disturbed environments since ephemeral herbs and grasses are rapid post-fire colonisers (Romme *et al.* 2011; Bell *et al.* 1993) and seeds are dropped *en masse* by many woody plants following fire events (Andersen 1988; Specht 1981). Crested Pigeons' efficacy in utilising these resources also contributes to their success in highly disturbed urban areas (Mulhall and Lill 2011). In contrast, many species with the lowest recolonisation rates were specialised on terrestrial invertebrates including Fan-tailed Cuckoo (*Cacomantis flabelliformis*) and Black-faced Monarch (*Monarcha melanopsis*). This may be due to the relative time taken for these resources to become large enough to support fauna species that are reliant on them (Purdie and Slatyer 1976). Increased seed availability from woody-fruited plants is believed to occur rapidly after a fire event (Andersen 1988). In contrast, terrestrial invertebrates may experience a greater lag in returning to pre-fire levels since insect grazing, which occurs at high rates in *Eucalyptus* forests (Springett 1978), must wait for sufficient regrowth before increasing biomass to pre-fire levels. Species with diets specialised on food that takes longer to recover from a fire event may be more deserving of management attention.

The massive firegrounds of the 2019-20 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 and 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 unburned 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, e.g., foraging for food or resting (Sullivan *et al.* 2009, 2014; Callaghan and Gawlik 2015; Johnston *et al.* 2020). Furthermore, the sampling effort for post-fire observations may have been greatly reduced due to a reduction in travel because of Coronavirus restrictions. Therefore, while citizen science data such as eBird are clearly valuable to inform macorecological 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 2019-20 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 and 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 would like to thank the 12,800 Australian eBirders that have provided the data that has made this project possible.

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. *Biodiversity and Conservation* **27**, 345–363.

Albanesi S., Dardanelli S. & Bellis L. M. (2014) Effects of fire disturbance on bird communities and species of mountain Serrano forest in central Argentina. *Journal of Forest Research* **19**, 105–114.

Andersen A. N. (1988) Immediate and longer-term effects of fire on seed predation by ants in sclerophyllous vegetation in south-eastern Australia. *Australian Journal of Ecology* **13**, 285–293.

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**.

Bell D. T., Plummer J. A. & Taylor S. K. (1993) *Seed germination ecology in southwestern Western Australia*.

Bird T. J., Bates A. E., Lefcheck J. S. *et al.* (2014) Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation* doi: 10.1016/j.biocon.2013.07.037. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2013.07.037.

Boer M. M., Resco de Dios V. & Bradstock R. A. (2020) Unprecedented burn area of Australian mega forest fires. *Nature Climate Change* **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.

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

Cary G., Bradstock R., Gill A. & Williams R. (2012) Global change and fire regimes in Australia. *Flammable Australia: Fire regimes, Biodiversity and Ecosystems in a Changing World*, 149–169. [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. *Biological Conservation* doi: 10.1016/j.biocon.2012.10.004. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2012.10.004.

Clarke H. & Evans J. P. (2019) Exploring the future change space for fire weather in southeast Australia. *Theoretical and Applied Climatology* **136**, 513–527.

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 (2018) 13: 9 (e0203694) DOI: 10.1371/journal.pone.0203694). *PLoS ONE* **14**, 1–13.

DAWE (2020) National Indicative Aggregated Fire Extent Datasets.

DPIE (2020a) *NSW Fire and the Environment 2019-20 Summary*.

DPIE (2020b) Fire Extent and Severity Mapping.

Eeden L. van, Nimmo D., Mahony M. *et al.* (2020) Australia's 2019-2020 Bushfires: The Wildlife Toll - Interim Report.

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. *Journal for Nature Conservation* **20**, 301–309. [online]. Available from: http://dx.doi.org/10.1016/j.jnc.2012.07.002.

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. *Journal of Safety Science and 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. *Scientific Data* doi: 10.1038/sdata.2015.61.

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 M. A. (1996) How Fires Affect Biodiversity. In: *Fire and Biodiverisy: The Effects and Effectiveness of Fire Management* Melbourne.

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

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

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* doi: 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. *Science of The Total Environment* doi: 10.1016/j.scitotenv.2020.142348. [online]. Available from: https://doi.org/10.1016/j.scitotenv.2020.142348.

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**, 1670–1680.

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. *Biological Conservation* **144**, 1663–1672. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2011.02.022.

Loyn R. H. (1997a) Effects of an extensive wildfire on birds in far eastern Victoria. *Pacific Conservation Biology* **3**, 221–234.

Loyn R. H. (1997b) Effects of an extensive wildfire on birds in far eastern Victoria. *Pacific Conservation Biology* **3**, 221–234.

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. *Biological Conservation* doi: 10.1016/j.biocon.2016.05.015. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2016.05.015.

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. *Biological Reviews* **94**, 981–998.

Nolan R. H., Boer M. M., Collins L. *et al.* (2020) Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Global Change Biology* **26**, 1039–1041.

van Oldenborgh G. J., Krikken F., Lewis S. *et al.* (2020) Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences*, 1–46.

Pausas J. G. & Parr C. L. (2018) Towards an understanding of the evolutionary role of fire in animals. *Evolutionary Ecology* **32**, 113–125. [online]. Available from: https://doi.org/10.1007/s10682-018-9927-6.

Pebesma E. (2018) Simple features for R: Standardized support for spatial vector data. *R Journal* **10**, 439–446.

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

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

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. *Biological Conservation* **215**, 268–276. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2017.09.005.

Purdie R. W. & Slatyer R. O. (1976) Vegetation succession after fire in sclerophyll woodland communities in south-eastern Australia. *Australian Journal of Ecology* **1**, 223–236.

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. *Forest Ecology and Management* doi: 10.1016/j.foreco.2014.01.008. [online]. Available from: http://dx.doi.org/10.1016/j.foreco.2014.01.008.

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**, 1196–1215.

Specht R. (1981) Heathlands. In: *Australian Vegetation* (ed R. Groves) pp. 253–275

Springett B. P. (1978) On the ecological role of insects in Australian eucalypt forests. *Australian Journal of Ecology* **3**, 129–139.

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. *Biological Conservation* doi: 10.1016/j.biocon.2013.11.003. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2013.11.003.

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. *Biological Conservation* **142**, 2282–2292. [online]. Available from: http://dx.doi.org/10.1016/j.biocon.2009.05.006.

Turner M. G., Baker W. L., Peterson C. J. & Peet R. K. (1998) Factors influencing succession: Lessons from large, infrequent natural disturbances. *Ecosystems* **1**, 511–523.

Ward M., Tulloch A. I. T., Radford J. Q. *et al.* (2020) Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology and Evolution* **4**. [online]. Available from: http://dx.doi.org/10.1038/s41559-020-1251-1.

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. *Journal of Open Source Software* **4**, 1686.

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

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

Tables and Figures

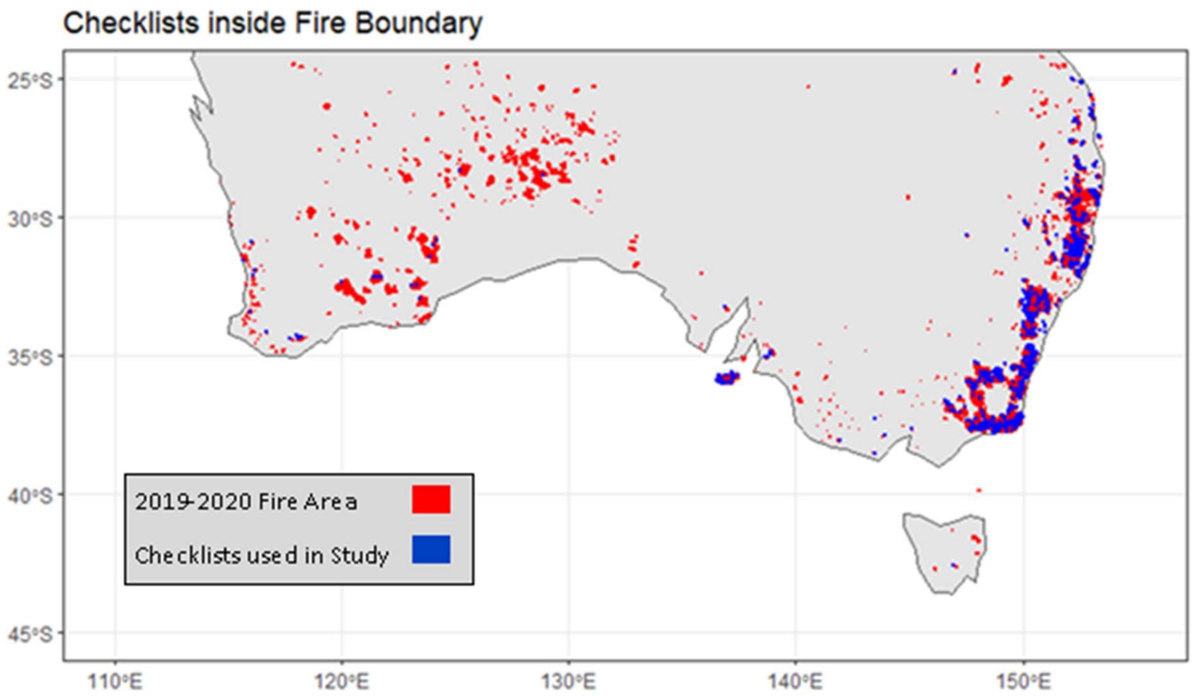

Figure 1- Map of burned area over the Australian 2019-20 summer fire event (Red) and eBird checklists inside fire boundary below 25 degrees South (Blue).

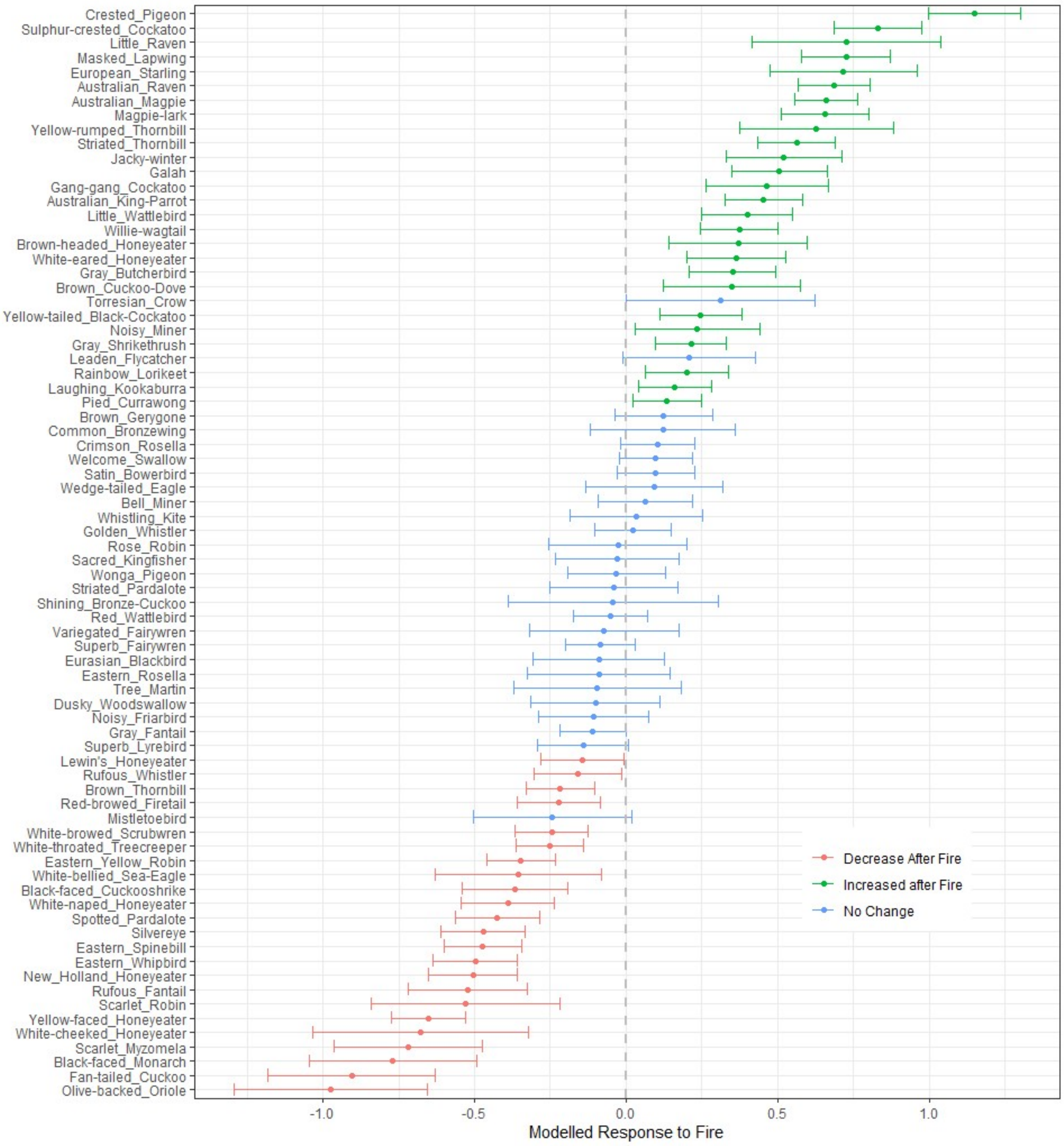

Figure 2- Ranked responses to fire as calculated by GAM models for each species, error bars represent standard error.

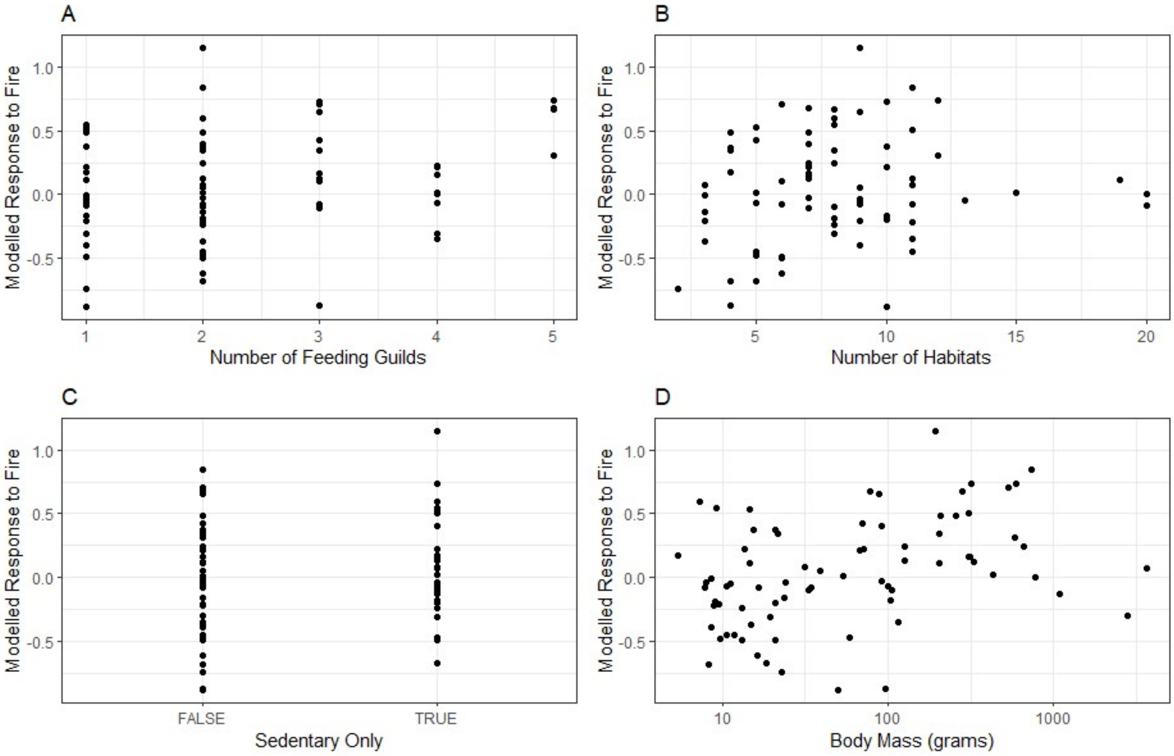

Figure 3- Plot of modelled fire response against degree of diet specialism (A), degree of habitat specialism (B), sedentism (C) and average body mass (log-transformed) (D), for each bird species.

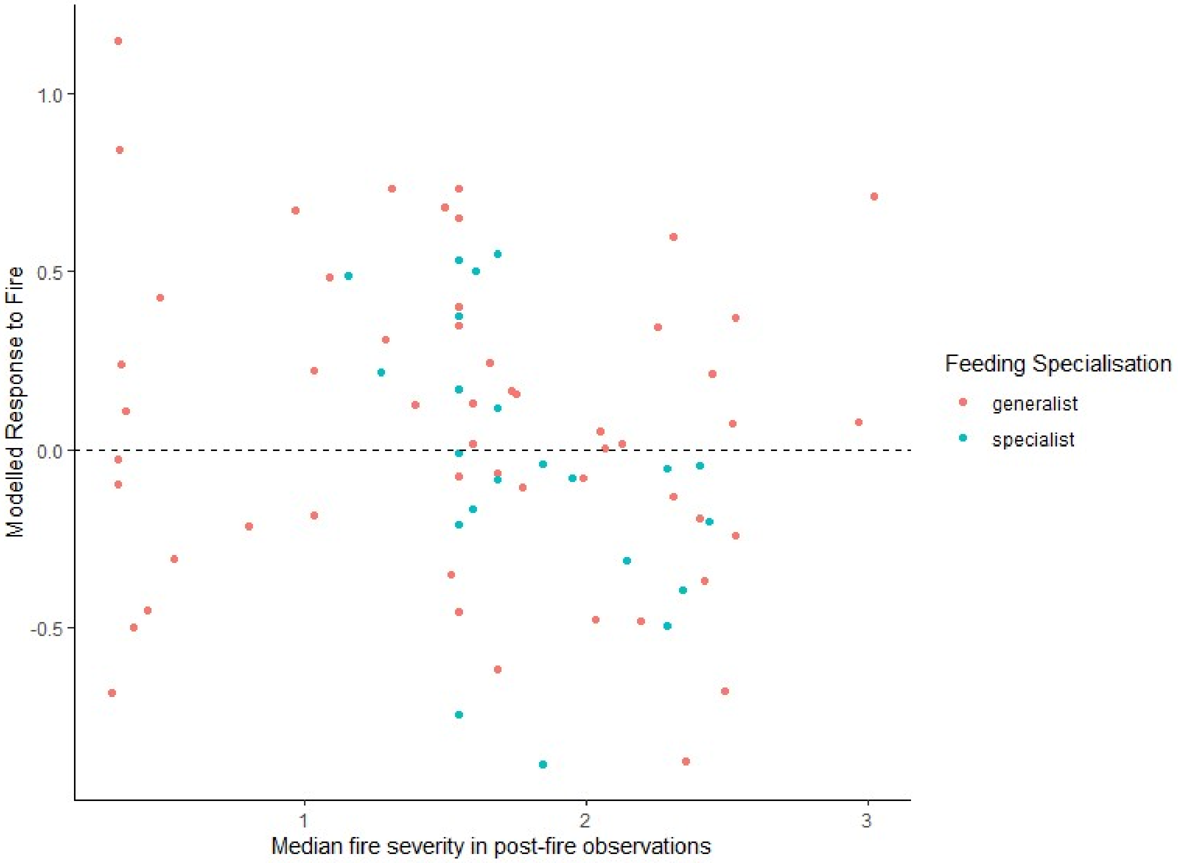

Figure 4- Scatterplot of modelled fire response against median fire severity grouped by feeding habit, where generalists are species belonging to more than one feeding guild. Interactive version at: https://josh-lee1.github.io/eBird-Fire-Index/interactive_figure.html