Science of the Total Environment 755 (2021) 142348

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short Communication

Rapidly mapping fire effects on biodiversity at a large-scale using citizen science

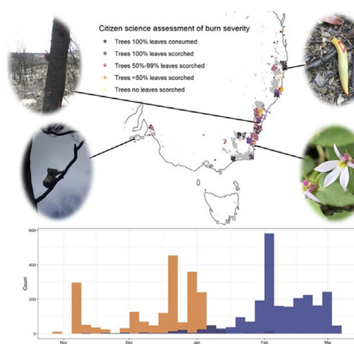
Casey Kirchhoff [a,*], Corey T. Callaghan [a,b], David A. Keith [a,c,d], Dony Indiarto [b], Guy Taseski [a], Mark K.J. Ooi [a,d], Tom D. Le Breton [a,d], Thomas Mesaglio [a], Richard T. Kingsford [a], William K. Cornwell [a,b]

[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
[c] NSW Department of Planning, Industry, and Environment, Sydney, NSW, Australia
[d] Bushfire Risk Management Research Hub, Wollongong, NSW, Australia

HIGHLIGHTS

- Monitoring the effects of large-scale disturbances on biodiversity can be challenging.
- Citizen scientists rapidly collected data on biodiversity responses following bushfires.
- Citizen scientists provided accurate data on fire severity.
- Data was collected on a wide range of biodiversity responses.
- Citizen science data was collected at a scale that matched the extent of the fires.

GRAPHICAL ABSTRACT



The unprecedented scale of the 2019-2020 eastern Australian bushfires exemplifies the challenges that scientists and conservation biologists face monitoring the effects of biodiversity in the aftermath of large-scale environmental disturbances. By working with the public, citizen science offers a unique opportunity to collect data on biodiversity responses. Our citizen science project, hosted on iNaturalist, found that citizen scientists provide rapid and accurate data on fire severity (colored dots on map), along with data from a wide range of biodiversity responses at a scale that matched the geographic extent of the fires (grey on map).

ARTICLE INFO

Article history:
Received 10 July 2020
Received in revised form 9 September 2020
Accepted 9 September 2020
Available online 11 September 2020

Editor: Frederic Coulon

Keywords:
Citizen science
Fire ecology
iNaturalist
Fire temperature
Eucalypt forests, rainforests

ABSTRACT

The unprecedented scale of the 2019–2020 eastern Australian bushfires exemplifies the challenges that scientists and conservation biologists face monitoring the effects on biodiversity in the aftermath of large-scale environmental disturbances. After a large-scale disturbance, conservation policy and management actions need to be both timely and informed by data. By working with the public, often widely spread out over such disturbed areas, citizen science offers a unique opportunity to collect data on biodiversity responses at the appropriate scale. We detail a citizen science project, hosted through iNaturalist, launched shortly after the 2019–2020 bushfire season in eastern Australia. It rapidly (1) provided accurate data on fire severity, relevant to future recovery; and (2) delivered data on a wide range (mosses to mammals) of biodiversity responses at a scale that matched the geographic extent of these fires.

1. Introduction

The 2019–2020 eastern Australian bushfires garnered international attention, given their unprecedented scope, scale, and severity (Nolan et al., 2020), spanning ecosystems from southern Queensland to Kangaroo Island, South Australia, more than 1700 km away. The fires

* Corresponding author.
E-mail address: c.gibson@unsw.edu.au (C. Kirchhoff).

https://doi.org/10.1016/j.scitotenv.2020.142348

represent one large-scale example of the impacts of climate change in a rapidly changing Anthropocene, with environmental disturbance predicted to increase in intensity, severity, and rate of occurrence in a warming climate (Enright et al., 2015). Other large-scale environmental disturbances predicted to increasingly impact biodiversity under climate change include more severe droughts (Fensham et al., 2015), more intense cyclones (Cheal et al., 2017), increased flooding (Milly et al., 2002) and increased warming of oceans (Hughes et al., 2018). Quantifying the impacts of these extensive disturbances can help develop effective policies and management for promoting recovery and resilience of biodiversity (Hampe and Petit, 2005).

The Australian bushfires in the 2019–2020 season burnt more than 7 million hectares in the two most populous states of Australia alone (New South Wales (NSW) and Victoria) (www.rfs.nsw.gov.au; www.ffm.vic.gov.au), and a globally unprecedented 21% of the Australian 'temperate broadleaf and mixed' forest biome (Boer et al., 2020). In NSW, 37% of all rainforest and entire distributions of many species, including those listed as threatened, were burnt (NSW DPIE, 2020), while across Australia almost 3 billion individual animals are estimated to have been affected (WWF Australia, 2020). Inevitably, these bushfires will have large impacts on biodiversity given their size and severity. Understanding responses across the taxonomic spectrum requires a large range of data sources, given the wide-ranging effects of bushfires. Recovery will vary from rapid to possibly not at all, depending on both the species and the severity and magnitude of the fires, highlighting the importance of a rapid assessment in relation to local effects of fires (Bradstock, 2010). Such essential but complex information presents a major logistical challenge, traditionally reliant on professional scientists' availability and budgets (Bakker et al., 2010), which are limited relative to the immense scale of the fires. This highlights a challenge for most government agencies around the world: an ill-preparedness for robust and timely quantification and monitoring of biodiversity impacts and responses to large-scale environmental disturbances.

How can scientists surmount this challenge? Citizen science data, collected by volunteers collaborating with professional scientists (Jordan et al., 2011), are now widely used in biodiversity research, providing conservation information at broad spatial and temporal scales relevant for policy and management (Chandler et al., 2017). These citizen science data are also an increasingly valuable option for understanding rapid changes to biodiversity from landscape-scale environmental disturbances. Moreover, modern platforms can be rapidly utilized to respond to catastrophic events, although the data collected may not be as high quality as professional data. There are many biases associated with citizen science projects, generally related to the level of structure of a project (Kelling et al., 2019), but such citizen data can provide reliable information for biodiversity management (Kosmala et al., 2016; Burgess et al., 2017), especially when combined with other data sources. Nonetheless, it represents a new, scalable tool for responding to large-scale disturbance.

Our rapid-response citizen science project, launched in response to the 2019–2020 Australian bushfires, provided data on the biodiversity response at a scale relevant to the unprecedented size of the fires. Our objective here is to highlight how citizen science can be used to rapidly assess and ground-truth biodiversity impacts from ecological disturbances such as bushfires. We leveraged an existing data platform – iNaturalist – and social and mainstream media to successfully design and spread awareness of the citizen science project. The goal of our project was to rapidly understand the severity of the fires, the diversity of taxa affected, and their early postfire responses in eastern Australia. In this paper, we: (1) summarize uptake of the citizen science project and (2) compare citizen scientist observations on bushfire severity to satellite-derived measures of bushfire intensity. We also identify how future citizen science research outputs can be made accessible (open-access) for rapid influence of conservation policy and management.

2. Methods

2.1. iNaturalist project

iNaturalist (www.inaturalist.org) is a global citizen science project, launched by the California Academy of Sciences, with >48 million observations of >294 thousand identified taxa globally. Participants contribute observations (e.g., photos, sound recordings) of any living (or dead) organism, or trace thereof, through either the smart-phone app or website, with spatiotemporal coordinates and some geographic uncertainty captured. All records are then identified to the lowest possible taxonomic resolution by the participant who uploaded the sighting along with other participants on the platform as part of a consensus system. In our instance, we created a 'traditional project', constrained to the Australian continent in the 'projects' feature of iNaturalist, quickly launching our citizen science initiative, with reasonably wide media coverage, in response to the 2019–2020 Australian bushfires across south-east Australia. Citizen scientists can manually join projects and add their data in the form of geolocated records of biota, with 'projects' able to create their own observation fields. We developed five observation fields, with three related to life history and biodiversity. The fields were: plants (native reseeder, weed reseeder, native resprouter, weed resprouter, unsure); animals (native alive, feral alive, native dead, feral dead, track, scat, digging, feather, unsure) and; fungi and lichen substrate (soil, wood and leaf litter, rock, unsure). The final two observation fields related to landscape burn severity: tree burn height (not burnt, burnt at base, burnt between base and middle, burnt between middle and top, burnt to top) and tree leaves (no leaves scorched, <50% scorched, 50%–99% scorched, 100% scorched, 100% consumed). We set 'na' (not available) as the default for each observation field, as this required manual selection of appropriate categories and avoided applying incorrect fields to an observation. All identifications and observation fields could be entered either by citizen scientists or experts (i.e., project managers in this instance) after the fact. In the case of citizen scientists, these data were subsequently subject to expert review. We interacted with participants through the project journal and species' identification comment features.

2.2. Hotspot data

To examine how rapid citizen science compared with other rapid assessment methods, we used the Digital Earth Australia Hotspots data (https://hotspots.dea.ga.gov.au/). These data are part of a national bushfire monitoring system, using satellite sensors to provide spectral signatures of fire (i.e., hotspots). We downloaded spatiotemporal coordinates for sites aligned with citizen science biodiversity data, and associated hot spot measure of temperature above background. We used temperature as a proxy for the intensity of a fire, given its wide-spread availability, matching our citizen science observations, and its fundamental role in remotely-sensed fire radiative power (Wooster et al., 2005). Our post-fire citizen science measure was categorical (i.e., burn severity), but nevertheless, we expected a correspondence between these two rapid measures.

2.3. Statistical analysis

We compared the categorical measure of burn severity reported by citizen scientists (i.e., no leaves scorched, <50% scorched, 50%–99% scorched, 100% scorched, 100% consumed; scorched leaves are visibly brown and retained on the tree) to the remotely-sensed temperature data. Both data sources included spatiotemporal coordinates; these were aggregated within buffers to produce a combination of thresholds at the spatial and fire severity level. We aggregated all points within specified buffer sizes, allowing for direct comparisons between the two datasets. We used a buffer size of 250 m, the optimal spatial scale for R^2 of model fit. In this analysis, we only included iNaturalist observations which provided a measure of burn severity (n = 1107 observations). We fitted a linear model with temperature as the response variable and our categorical burn severity level as the predictor variable. To make comparisons among the different categorical levels used as a predictor variable, we used effect sizes for the pairwise differences, extracted using the 'emmeans' package in R. Because of the likely spatial autocorrelation in the citizen science observations, we also fitted two different spatial models (GLS and glmmfields) to ensure the robustness. Both these approaches confirmed our linear model results; we present only the linear model results here. To corroborate our correlation with hotspot data, we also tested our results against a measure of remotely-sensed fire severity, the Fire Extent and Severity Mapping product (Gibson et al., 2020). It is at 10 m resolution requiring us to aggregate its data to 100 m resolution to better match the spatial uncertainty of iNaturalist observations. This additional investigation was restricted to New South Wales only. Lastly, we mapped the area of national vegetation formations (Keith, 2017) across south-eastern Australia, defined here as temperate to subtropical biomes within the south eastern states (Hobbs and McIntyre, 2005; Hutchinson et al., 2020), that were burnt using the National Indicative Aggregated Fire Extent dataset, and compared it with our citizen science data. All data were processed in R software (R Core Team, 2020).

2.4. Data availability

All data are available through the citizen science project: https://www.inaturalist.org/projects/environment-recovery-project-australian-bushfires-2019-2020. Code and data pertaining to our analyses are available on GitHub: https://github.com/cornwell-lab-unsw/aus_fires_data. The National Indicative Aggregated Fire Extent Dataset is available here: http://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B9ACDCB09-0364-4FE8-9459-2A56C792C743%7D. The Fire Extent and Severity Mapping product is available here: https://data.gov.au/dataset/ds-nsw-c28a6aa8-a7ce-4181-8ed1-fd221dfcefc8/details?q=.

3. Results

A total of 3265 observations, from 240 unique users, were submitted to the iNaturalist citizen science project (30 January 2020–16 March 2020), spanning nearly 51 million ha (Fig. 1, minimum convex polygon). Of these observations, 51.1% of users added extra fields to the citizen science observations. The observations included plants (73.7%), animals (21.5%), and fungi (4.6%), totalling 688 identified species, 255 families, and 98 orders (Fig. 2). Of the 610 animal observations, 376

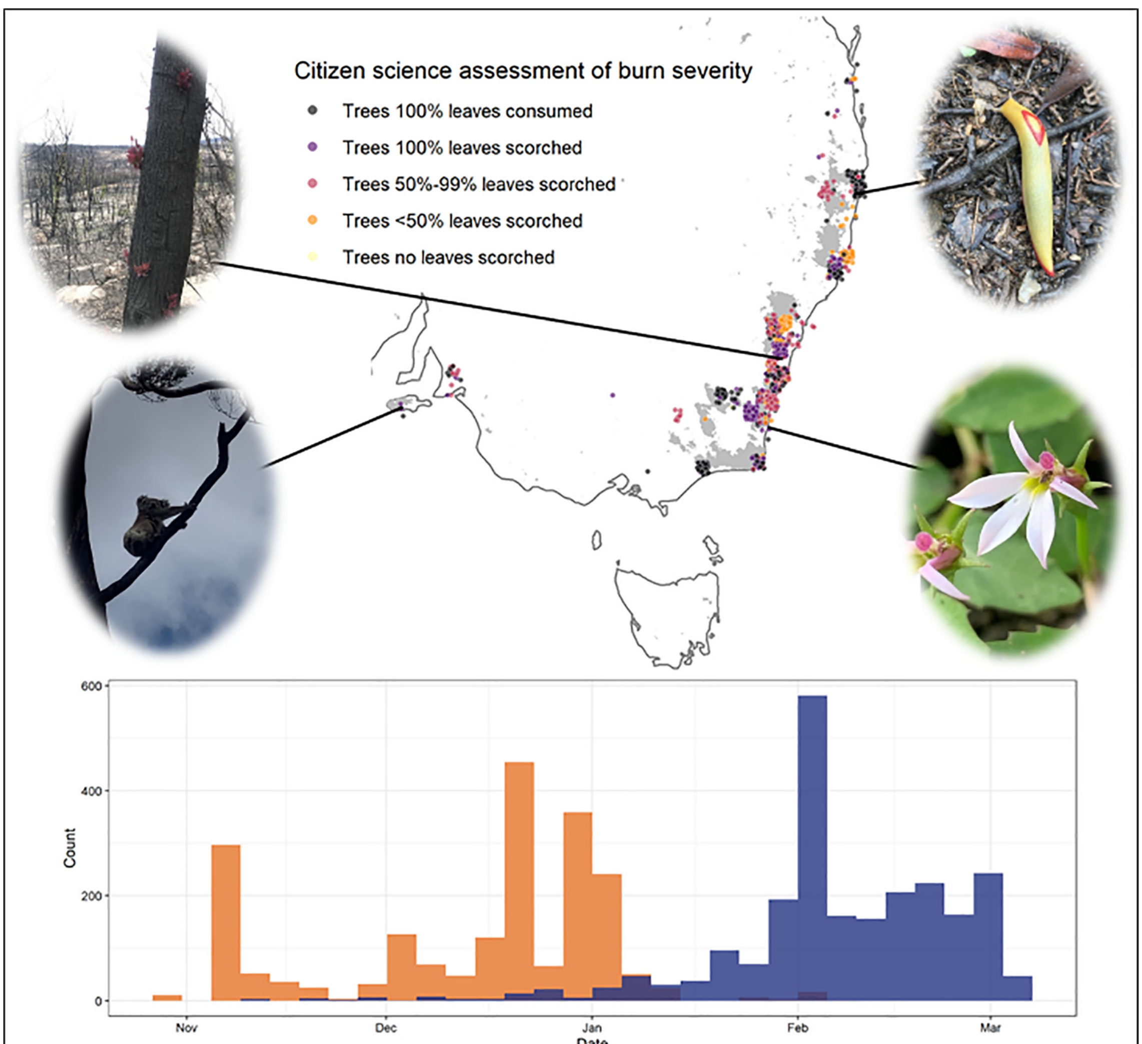


Fig. 1. Map of fire extent (grey regions) in eastern Australia, with our citizen science derived measures of on ground burn severity (including four photographic observations and their contributors, top left burnt Eucalyptus: *motherj*; bottom left Koala: *tonia1971*; top right Red Triangle Slug: *mollynuge*; bottom right White Root: *gtaseski*) and a comparison between the timing of the fire front extent, measured in terms of numbers of hotspot data (red), and number of citizen science observations (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

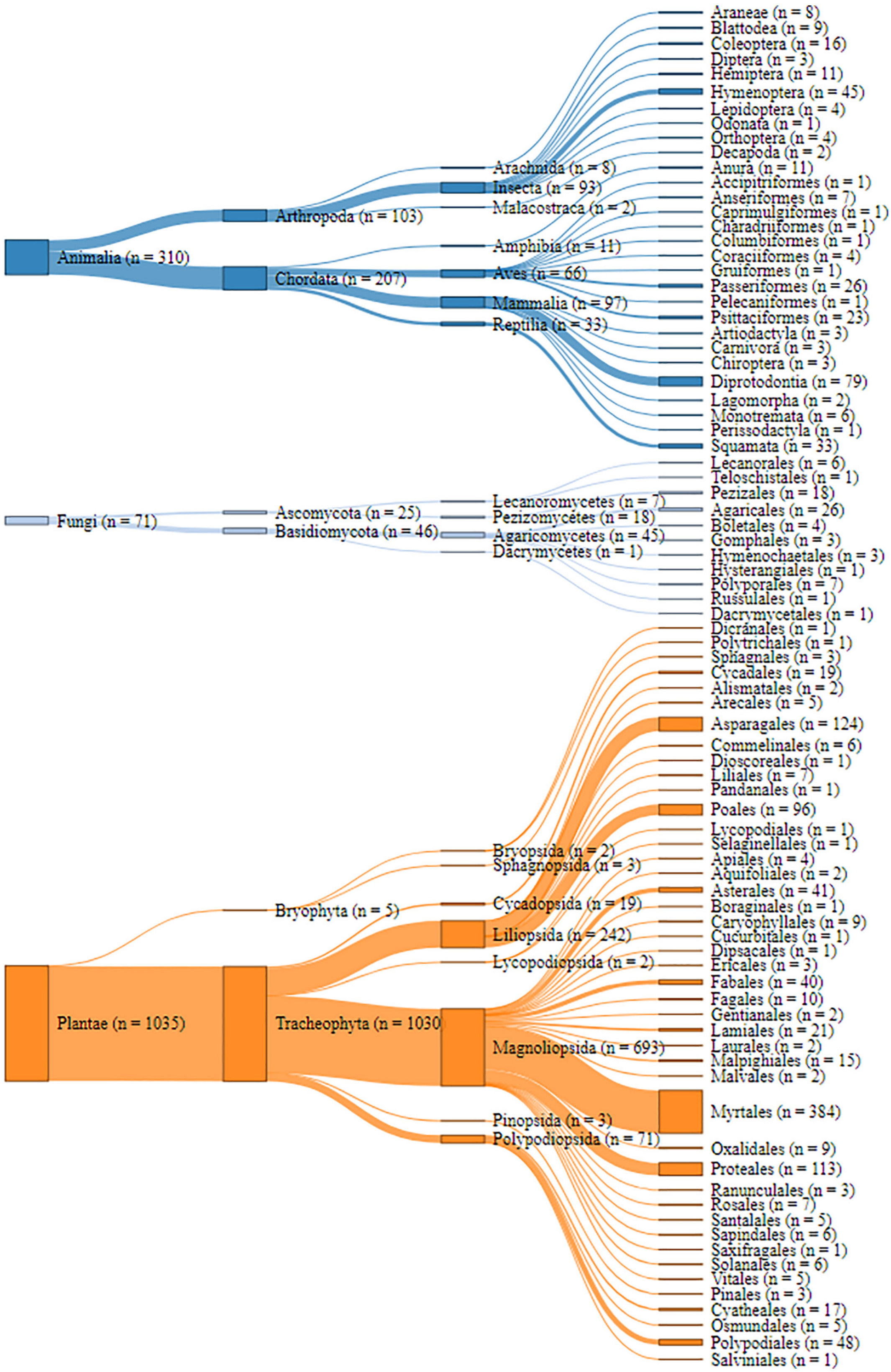


Fig. 2. Taxonomic breakdown (kingdom, phylum, class, and order) and the number of identified observations (71% of the total observations were identified to order). Two slime molds added to the project but are not shown here.

were vertebrates and 234 were invertebrates. Of the animals, the most commonly observed taxa were insects (208), mammals (143), and birds (136). For plants, Myrtales (674, e.g., *Eucalyptus* and *Melaleuca*), Asparagales (214, e.g., orchids and grass trees), and Proteales (216, e.g., *Banksia* and *Hakea*) were the top three most commonly reported taxa. Among the other 132 observations, there were 36 Ascomycota,

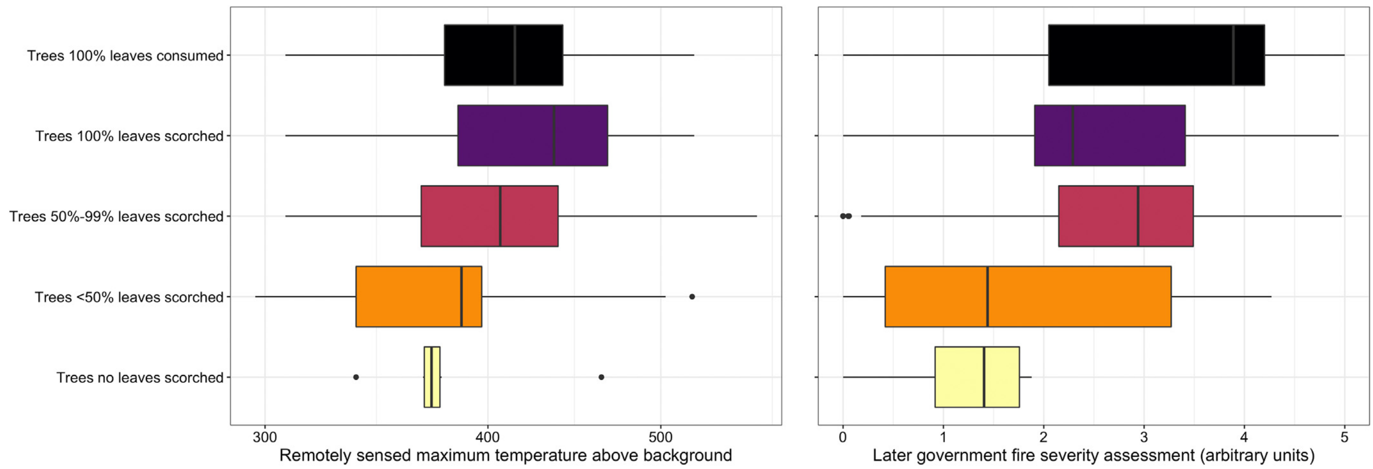


Fig. 3. Relationship between the citizen science measure of burn severity and the remotely sensed temperature from the Digital Earth Australia hotspots data (left panel). Relationship between citizen science measure and a later government assessment of burn severity from sites within New South Wales. Note that the units are arbitrary with severity increasing towards higher values. This spatially explicit severity assessment took several months to produce and refine.

94 Basidiomycota, and 2 slime molds. Mammals were the most commonly observed dead individuals (N = 6), mostly: *Macropus* (kangaroos and wallabies), *Pteropus* (flying foxes), *Vombatus* (wombats), and *Wallabia* (wallabies). Birds, insects, reptiles, amphibians, and a variety of non-native mammals were also observed dead throughout the firegrounds. One complication with observations of dead individuals from severely burned areas was that, in many cases, species' identifications were often was not possible from photographs alone, making interpretation difficult. It is also difficult to know whether these individuals were killed directly or indirectly by the fire, or from other causes. While these observations are patchy and difficult to identify, they provide some evidence of where and when the fires were the deadliest for specific taxa.

Our categorical citizen science measure of burn severity correlated well with the continuous measure of remotely sensed temperature of the fires (Fig. 3). Pairwise effect sizes showed that 'trees 100% scorched' had larger effect sizes than all other categories, followed by 'trees 100% consumed', whereas trees 'no leaves scorched' had the smallest pairwise effect size in all instances (Table S1). To test the utility of the data generated, we developed a case study using resprouting plants. We assessed how the number of resprouting plant observations (our response variable) compared with burn severity estimated by citizen scientists, and expected a negative relationship with increasing severity. Of the 461 observations which were tagged as native resprouters, we found that 1 was associated with a record of 'no leaves scorched', 78 with 'trees <50% scorched', 155 with 'trees 50-99% leaves scorched', 123 with 'trees 100% scorched', and 104 with 'trees 100% consumed'.

We found that Wet Sclerophyll forests had the highest percentage of burnt habitat in south-east Australia (31.48%), followed by Dry Sclerophyll Forests (19.85%) (Fig. 4). Importantly, fire sensitive vegetation types also had a high percentage of burnt area, including Rainforest (15.63%), followed by Freshwater wetlands, including swamps, (7.4%). The distribution of iNaturalist observations across vegetation formations did not adequately reflect the vegetation communities burned and was dominated by those in Dry Sclerophyll Forest (n = 1502), followed by Temperate subhumid woodlands (n = 400) and Wet Sclerophyll Forest (n = 349). Among the fire sensitive vegetation formations, observations were relatively few and similarly unrelated to percentage of burnt area, with Freshwater wetlands (n = 136) having more than 4 times the number of observations as Rainforests (n = 29).

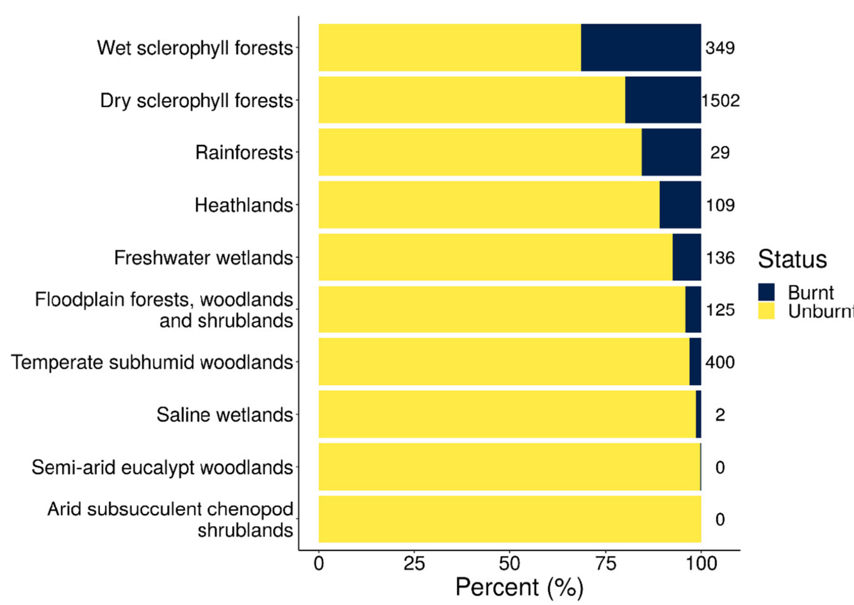


Fig. 4. Percentage of burnt and unburnt area of affected national vegetation formations across temperate-subtropical south-east Australia during the 2019–2020 fire season. The number to the right of each bar indicates the number of iNaturalist observations recorded within that vegetation formation.

4. Discussion

The enormous scale of the 2019–2020 fire season in eastern Australia presents a challenge for scientists, including conservation biologists, policy-makers, and managers. Informed decisions about prioritising management or conservation need to be based on the best available evidence, and usually quickly, for a rapid and effective recovery response (Kooyman et al., 2020). However, the scale of the 2019–2020 bushfires, and many other large-scale disturbances likely to increase in frequency in the future, was simply too big for a rapid response using conventional biodiversity monitoring methods, such as on-the-ground observations by trained professionals, given resourcing constraints (human and financial). These more detailed approaches are needed for more targeted learning and management planning, but are not well-suited for rapid, large-scale sampling.

Citizen science will play a key role in biodiversity monitoring for these and future fires of this magnitude. Because citizen scientists were already spread out across the impacted areas, they could be mobilized without logistical constraints and could sample disparate parts of the firegrounds, producing large-scale datasets quickly (Fig. 1). These provided both fire severity information but also basic occurrence data on the recovery of a wide range of biota. As expected, our case study assessing how number of observations of resprouting plants compared to burn severity, showed a negative relationship, with the most resprouter observations recorded at medium severities and very few at low severities, and a marginal decrease from medium to extreme severity areas. While further work is needed to explore the drivers of this relationship (e.g., temporal delay of recovery), this assessment can highlight where resources should be directed for on-ground assessment. However, as with all citizen science projects, effort was generally haphazard in spatial and temporal sampling: the sampling is not complete, and spatially and temporally biased. For example, there are likely biases in regards to citizen scientists uploading photographs of resprouters in different severity levels (i.e., more likely to notice a resprouter in a high severity burnt area than a low severity burnt area). These are limitations that can be offset by targeted investments in more systematic monitoring projects (Legge et al., 2018). Other limitations of these citizen science data include the spatial accuracy of submitted observations, and the identification of species. The bias of the former can be minimized by including strict filters, such as removing observations with coarse spatial accuracy. For species' identifications, iNaturalist uses a community-based identification process with relatively high reliability, comparable with that of experts (Hochmair et al., 2020; Uyeda et al., 2020). Further, within our project, experts verified identities of most biodiversity observations. Nevertheless, some taxa (e.g., grasses, sedges, ants, bees) were difficult, or impossible, to identify from photographs alone, a limitation of the iNaturalist platform. Despite the potential limitations, these citizen science data occurred at the scale commensurate with the fires, providing an opportunity for scientists to collaborate, cross-validate, and gap-fill these citizen science data to ensure a robust and comprehensive sample of the event and associated phenomena. And by combining citizen science data with other data, including remotely sensed products, understanding can improve for some of the processes involved and likely opportunities for recovery of organisms and their ecosystems.

Fire scientists typically quantify fire regimes, including the intensity (i.e., the energy output from the fire itself) and extent of fires in space and time, as well as the severity of the burn (i.e., the organic matter lost by component organisms as a direct result of the fire). Estimates of severity and intensity are both useful for understanding fire behaviour and its different impacts on functional processes or potential for recovery (Keeley, 2009). These two indices are positively correlated, but can be related weakly to each other because of different vegetation physiognomies and fuel characteristics (Hammill and Bradstock, 2006). We showed a similar positive relationship between our citizen science-generated assessment of fire severity and intensity measured remotely, as well as later assessment of severity from a variety of data sources (Fig. 3). One advantage of on-the-ground observations, including those in this study, is that ground observers can more clearly see the effects of surface fires where the canopy is unaffected. This is consistent with the argument of Gibson et al. (2020) who used a different mapping platform, and reinforced the need for ground observations. The strength of the relationship we found was likely to be reduced in particular vegetation types, for example tall forests with a low intensity surface fire, and is also limited by outliers resulting from spatiotemporal gaps in the satellite data, which sometimes miss the peak intensity of a given fire. Importantly, the on-ground validation data from citizen scientists were useful in ground-truthing broad-scale fire severity (Gibson et al., 2020). Finer-resolution remote sensing products are, however, the result of machine learning algorithms that require training data (e.g., Gibson et al., 2020), a process that is fire-specific and takes time to produce. A reliable understanding of fire severity patterns is important to guide immediate post-fire response efforts, such as wildlife rescue, as well as longer term strategic policies centred on protection of fire refuges and reducing risks of future fires. Citizen science observations support this effort by enabling policy decisions to be informed by a stronger and more timely understanding of the uncertainties in mapping than is possible by other means.

We learnt a few key things through developing, implementing, and running this project. First, citizen scientists need to know that the project exists and so opportunities to publicise the project on mainstream media and social media are important; we had significant spikes in engagement following stories on mainstream media. Second, it was essential to keep citizen science participants updated about the project (e.g., number of observations, species identified), given their eagerness for information. We provided feedback through the use of journal posts in the iNaturalist platform. Such feedback is critical to a project's success (de Vries et al., 2019). Third, some participants increased their learning during the project, evidenced by their improved identifications after learning identifications from interactions with experts on the iNaturalist platform, similar to other citizen science projects (Jordan et al., 2011; Phillips et al., 2018). Lastly, scientists wanting to broaden their research with citizen science should capitalize on already-existing platforms with an existing user-base (e.g., iNaturalist). This allows for rapid and efficient collection of data, without costly financial and time overheads of development, programming, and implementation. This is particularly important in the context of collecting data in a short time-frame in response to ecological disturbances such as bushfires.

Two other features of this project are worth highlighting. First, the public platform ensures the dataset is open and can be downloaded and analyzed by professional or citizen scientists. This is crucial given the wide range of taxa surveyed (Fig. 2) and the potential utility for data for taxa specialists. Second, the data could be linked to pre-fire data – collected at the same sites and sometimes by the same observers – allowing analyses of population, species, and community responses to bushfires.

Citizen science data can significantly contribute to the data we require to make decisions, particularly over large temporal and spatial scales (Chandler et al., 2017; Callaghan et al., 2019). Our project delivered rapid data on biodiversity and fire severity over a large scale. Uniquely, we demonstrated the utility of citizen scientists to respond to landscape-scale environmental disturbances such as the 2019–2020 fires in southeastern Australia. The challenge will be to continue to engage citizen scientists to collect data tracking long-term temporal change over such a large spatial scale. This can be partly met by showing how these data can significantly improve understanding of fire processes and also contribute to improving the management of the environment for the many organisms affected by such large scale fires. Citizen science is now entering an era where the platforms can rapidly mobilize data collection after large-scale catastrophic events, which are expected to be more frequent due to anthropogenic change to the atmosphere and climate (Cheal et al., 2017).

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142348.

CRediT authorship contribution statement

Casey Kirchhoff: Project conceptualisation, Project moderation, Writing. **Corey T. Callaghan:** Data curation, Methodology, Writing-Original draft preparation. **David A. Keith:** Writing, Reviewing, Editing. **Dony Indiarto:** Data visualisation. **Guy Taseski:** Project moderation. **Mark K. J. Ooi:** Methodology, Writing, Reviewing, Editing. **Tom D. Le Breton:** Writing, Reviewing, Editing. **Thomas Mesaglio:** Project moderation, Writing, Editing. **Richard T. Kingsford:** Writing, Reviewing, Editing, Supervision. **William K. Cornwell:** Project moderation, Data curation, Methodology, Writing, Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the naturalists who are greatly increasing our knowledge on biodiversity responses to fire and contributing their observations to iNaturalist. MKJO and DAK thank the NSW Government's Department of Planning, Industry and Environment for providing funds to support their research via the Bushfire Risk Management Research Hub. This paper is part of Project No. GA-2000224 from the Australian Government Department of Agriculture, Water and the Environment's 'Wildlife and Habitat Bushfire Recovery Program 2019-20'.

References

Bakker, Victoria J., et al., 2010. The changing landscape of conservation science funding in the United States. Conserv. Lett. 3 (6), 435–444. https://doi.org/10.1111/j.1755-263x.2010.00125.x.

Boer, Matthias M., et al., 2020. Unprecedented burn area of Australian mega forest fires. Nat. Clim. Chang. 10, 170–172. https://doi.org/10.1038/s41558-020-0716-1.

Bradstock, Ross A., 2010. Flammable Australia the Fire Regimes and Biodiversity of a Continent. Cambridge Univ. Press.

Burgess, H.k., et al., 2017. The science of citizen science: exploring barriers to use as a primary research tool. Biol. Conserv. 208, 113–120. https://doi.org/10.1016/j.biocon.2016.05.014.

Callaghan, Corey T., et al., 2019. Improving big citizen science data: moving beyond haphazard sampling. PLoS Biol. 17 (6). https://doi.org/10.1371/journal.pbio.3000357.

Chandler, Mark, et al., 2017. Contribution of citizen science towards international biodiversity monitoring. Biol. Conserv. 213, 280–294. https://doi.org/10.1016/j.biocon.2016.09.004.

Cheal, Alistair J., et al., 2017. The threat to coral reefs from more intense cyclones under climate change. Glob. Chang. Biol. 23 (4), 1511–1524. https://doi.org/10.1111/gcb.13593.

de Vries, M., Land-Zandstra, A., Smeets, I., 2019. Citizen scientists' preferences for communication of scientific output: a literature review. Citizen Sci. Theory Pract. 4, 1–13. https://doi.org/10.5334/cstp.136.

Enright, N.J., Fontaine, J.B., Bowman, D.M.J.S., Bradstock, R.A., Williams, R.J., 2015. Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. Front. Ecol. Environ. 13 (5), 265–272.

Fensham, Roderick J., et al., 2015. Dominant tree species are at risk from exaggerated drought under climate change. Glob. Chang. Biol. 21 (10), 3777–3785. https://doi.org/10.1111/gcb.12981.

Gibson, Rebecca, et al., 2020. A remote sensing approach to mapping fire severity in south-eastern Australia using sentinel 2 and random forest. Remote Sens. Environ. 240, 111702. https://doi.org/10.1016/j.rse.2020.111702.

Hammill, Kate A., Bradstock, Ross A., 2006. Remote sensing of fire severity in the Blue Mountains: influence of vegetation type and inferring fire intensity. Int. J. Wildland Fire 15 (2), 213. https://doi.org/10.1071/wf05051.

Hampe, Arndt, Petit, Rémy J., 2005. Conserving biodiversity under climate change: the rear edge matters. Ecol. Lett. 8 (5), 461–467. https://doi.org/10.1111/j.1461-0248.2005.00739.x.

Hobbs, R.J., McIntyre, S., 2005. Categorizing Australian landscapes as an aid to assessing the generality of landscape management guidelines. Glob. Ecol. Biogeogr. 14 (1), 1–15.

Hochmair, H.H., Schefrahn, R.H., Basille, M., Boone, M., 2020. Evaluating the data quality of iNaturalist termite records. PLoS One 15 (5), e0226534. https://doi.org/10.1371/journal.pone.0226534.

Hughes, Terry P., et al., 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359, 80–83. https://doi.org/10.1126/science.aan8048.

Hutchinson, M.F., McIntyre, S., et al., 2020. Integrating a global agro-climatic classification with bioregional boundaries in Australia. Glob. Ecol. Biogeogr. 14 (3), 197–212.

Jordan, Rebecca C., et al., 2011. Knowledge gain and behavioral change in citizen-science programs. Conserv. Biol. 25 (6), 1148–1154. https://doi.org/10.1111/j.1523-1739.2011.01745.x.

Keeley, Jon E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18 (1), 116. https://doi.org/10.1071/wf07049.

Keith, David A., 2017. Australian Vegetation. Cambridge University Press, Cambrdge.

Kelling, Steve, et al., 2019. Using semistructured surveys to improve citizen science data for monitoring biodiversity. BioScience 69 (3), 170–179. https://doi.org/10.1093/biosci/biz010.

Kooyman, Robert M., et al., 2020. Protect Australia's Gondwana rainforests. Science 367 (6482). https://doi.org/10.1126/science.abb2046.

Kosmala, Margaret, et al., 2016. Assessing data quality in citizen science. Front. Ecol. Environ. 14 (10), 551–560. https://doi.org/10.1002/fee.1436.

Legge, Sarah M., et al., 2018. Monitoring Threatened Species and Ecological Communities. CSIRO Publishing, Melbourne.

Milly, P.C.D., et al., 2002. Increasing risk of great floods in a changing climate. Nature 415 (6871), 514–517. https://doi.org/10.1038/415514a.

Nolan, Rachael H., et al., 2020. Causes and consequences of eastern Australia's 2019–20 season of mega-fires. Glob. Chang. Biol. https://doi.org/10.1111/gcb.14987.

NSW DPIE (Department of Planning, Industry and Environment), 2020. Understanding the effects of the 2019-20 fires. https://www.environment.nsw.gov.au/topics/parks-reserves-and-protected-areas/fire/park-recovery-and-rehabilitation/recovering-from-2019-20-fires/understanding-the-impact-of-the-2019-20-fires.

Phillips, T., Porticella, N., Constas, M., Bonney, R., 2018. A framework for articulating and measuring individual learning outcomes from participation in citizen science. Citizen Sci. Theory Pract. 3, 1–19. https://doi.org/10.5334/cstp.126.

R Core Team, 2020. R: A language and environment for statistical ## computing. R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org/.

Uyeda, K.A., Stow, D.A., Richart, C.H., 2020. Assessment of volunteered geographic information for vegetation mapping. Environ. Monit. Assess. 192, 554. https://doi.org/10.1007/s10661-020-08522-9.

Wooster, M.J., et al., 2005. Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. J. Geophys. Res. Atmos., 110 https://doi.org/10.1029/2005JD006318.

WWF Australia, 2020. Australia's 2019-2020 bushfires: the wildlife toll. Accessed here. https://www.wwf.org.au/news/news/2020/3-billion-animals-impacted-by-australia-bushfire-crisis#gs.e1ic23.