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Fire ecology for the 21st century

Conserving biodiversity in the age of megafire

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Published in:
Diversity and Distributions

DOI:
[10.1111/ddi.13482](https://doi.org/10.1111/ddi.13482)

Published: 01/03/2022

Document Version
Publisher's PDF, also known as Version of record

[Link to publication](#)

Citation for published version (APA):

Nimmo, D. G., Andersen, A. N., Archibald, S., Boer, M. M., Brotons, L., Parr, C. L., & Tingley, M. W. (2022). Fire ecology for the 21st century: Conserving biodiversity in the age of megafire. *Diversity and Distributions*, 28(3), 350-356. <https://doi.org/10.1111/ddi.13482>

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Fire ecology for the 21st century: Conserving biodiversity in the age of megafire

1 | BIODIVERSITY CONSERVATION IN THE AGE OF MEGAFIRE

Fire is one of Earth's most potent agents of ecological change. This Special Issue comes in the wake of a series of extreme wildfires across the world, from the Amazon, to Siberia, California, Portugal, South Africa and eastern Australia (Duane et al., 2021). These "megafires," variously defined according to their size, intensity, or impacts (Attiwill & Binkley, 2013), are perhaps the signature feature of Earth's fiery transition to what Pyne (2020) has termed the "Pyrocene." Projections of increased fire weather and extended fire seasons portend an increasingly flammable planet (Ellis et al.; Jain et al., 2021; Wu et al., 2021).

Recent megafires have alarmed conservation scientists and practitioners because their scale and intensity demands new ways of thinking about biodiversity conservation in fire-prone landscapes, and, potentially, new tools tailored to avoid or minimise fire-induced declines and extinctions (Wintle et al., 2020). Megafires have the potential to transform landscapes at a speed and scale unmatched by most abiotic disturbances. Urgent questions remain regarding how ecosystems are affected by, and recover from, megafires (Jolly et al., 2022); the effectiveness of interventions aimed at minimising decline and promoting recovery of species, communities, and ecosystems following megafire (Wintle et al., 2020); how to best monitor the ecological impacts of megafire, and how to prioritise conservation investment within increasingly massive fire footprints (Southwell et al., 2022). This Special Issue of *Diversity and Distributions* grapples with some of these complexities and challenges.

The 2019–20 Australian megafires feature prominently in this Special Issue. These fires were unprecedented in more ways than one: fanned by unprecedented climatic conditions (Abram et al., 2021), they burned an unprecedented percentage of a continental forest biome (Boer et al., 2020), including an unprecedented area of high severity fire (Collins et al., 2021). They burned habitat for >3 billion individuals of >800 species of vertebrates (Van Eeden et al., 2020; Ward et al., 2020), including some species with entire geographic ranges encompassed by the fires (Legge et al., 2022). Hundreds of species are having their conservation status reviewed because of this single "season in hell" (Wintle et al., 2020). This Special Issue provides an opportunity to reflect upon the potential

impacts of those fires, and the lessons learned that will be relevant to other regions grappling with megafires (Geary et al., 2022; Legge et al., 2022), while also contrasting Australia's experience with other record-breaking recent fire seasons (e.g., California).

2 | FIRE ECOLOGY: FROM TEMPORAL TO SPATIOTEMPORAL

Fire is an inherently spatiotemporal process, yet fire ecology has, for much of its history, been more concerned with the temporal than the spatial effects of fire—with a particular focus on local post-fire successional trajectories of species and communities (Keith, 2021). Studies in this Special Issue provide examples of the insights that temporal studies of fire can provide: Connell et al. (2022) showed that species' post-fire responses are contingent on prevailing climatic conditions; Miller et al. (2022) demonstrated the surprisingly long-term (100+ year) post-fire successional dynamics of lichen communities; Rainsford et al. (2022) revealed the variable successional trajectories of different functional groups of plants and birds, and how that information can be used to assess tolerable minimum and maximum fire intervals, and; Topp et al. (2022) showed that the response of butterflies to fire depends on species' mobility, mediated through the effects of fire on vegetation structure.

In the last decade, the impacts of spatiotemporal measures of fire, such as "pyrodiversity"—the diversity of fire histories across space—have become major foci (Furnas et al., 2022; Parr & Andersen, 2006; Taylor et al., 2012). Pyrodiversity has received particular attention because of the hypothesis that a diversity of fire histories would increase biodiversity (Martin & Sapsis, 1992). Yet, the multi-dimensional nature of the fire regime—encompassing fire frequency, interval, seasonality, intensity, severity and spatial aspects (size, extent, configuration)—gave rise to a proliferation of pyrodiversity concepts (Bowman, Perry, et al., 2016; Hempson et al., 2018; Kelly et al., 2016) and an equally diverse array of approaches to examine the relationships between pyrodiversity and biodiversity (Jones & Tingley, 2022).

Jones and Tingley (2022) make a significant contribution by defining criteria for direct tests of the "pyrodiversity begets biodiversity" hypothesis. The most important feature is that measurements

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of pyrodiversity are captured *within* the observational unit of the study, not *among* them. While there remain many obstacles to resolving whether, where, and when pyrodiversity promotes biodiversity, clear criteria for what constitutes a test of the hypothesis represent a substantial move forward. The next steps will be clarifying and unifying metrics of pyrodiversity across studies, a greater consideration of the role of spatial scale in studies of the relationship between pyrodiversity and biodiversity (Jones & Tingley, 2022), and consideration of how contemporary pyrodiversity compares to pyrodiversity maintained under fire regimes to which biota have adapted, especially Indigenous fire regimes (Greenwood et al., 2021).

In the context of megafires, the importance of spatial aspects of fire become painfully obvious, but the mechanisms facilitating the recovery of biodiversity following megafires remain uncertain. Models of post-fire recovery of animals emphasise three potential pathways: *in situ* recovery, driven by fire survivors within the burned landscape; *ex situ* recovery, driven by colonisation from outside of the fire footprint; and nucleated recovery, driven by survivors in fire refuges (Banks et al., 2011, 2017). Megafires can create landscapes in which the potential sources of *ex situ* recovery—organisms outside of the fire footprint—are tens of kilometres removed from fire-affected points of the landscape (Collins et al., 2021), and in which few refuges remain within the fire boundary to allow nucleated recovery, potentially hampering or slowing post-fire recovery (Nimmo et al., 2019). Bradstock (2008) highlighted that, contrary to popular opinion, recovery of plant species from large fires can often be driven internally, by *in situ* survivors. Recent work from Australia's 2009 Black Saturday fires confirmed the surprising importance of *in situ* survivors for animal recovery too (Banks et al., 2011, 2017).

In this Special Issue, Hale et al. (2022) provide further evidence of within-fire survival being the impetus of recovery for small mammals following a series of large wildfires in south-eastern Australia. In the aftermath of the fires, there was no relationship between the occurrence of several mammal species and distance to potential sources of recovery. Instead, features that could provide an internal refuge—rocks and large trees—were related to species' occurrence within the fire footprint. In contrast to Hale—but encompassing a longer successional time-scale—Steel et al. (2022) identify a clear spatial gradient in richness and composition of Californian bird communities driven by distance to the edge of high severity patches: communities near the interior of high severity patches differed from those near the edge, with the former being comprised disproportionately of ground- and shrub-nesting species, and relatively fewer tree and cavity-nesting species. They also show that the richness of bird communities decreases with the size of patches that burned at high severity, due to the loss of tree and cavity-nesting species. Given the increasing regularity of large, severe fires in California (Keeley & Syphard, 2021), Steel et al. (2022) warn of the substantial changes in bird community composition that shifting fire regimes could deliver. In an important contribution, Calhoun et al. (2022) illustrate that such impacts have already spread well beyond the conifer forest ecosystems where the political and media focus of recent Californian fires has typically centred.

3 | MONITORING MEGAFIRES

While manipulative experiments will always be the gold standard in many areas of ecology, including fire ecology (Andersen, 2021), there are processes that operate at spatial scales that make manipulation unethical or impossible (Barley & Meeuwig, 2017). Megafire is one of these processes. Our understanding of megafire will necessarily be derived from opportunistic studies that draw on Control-Impact or Before-After-Control-Impact (BACI) designs. Megafires that occur across part of an existing monitoring program provide an opportunity to deploy BACI designs (e.g., Jones et al., 2016), but the unpredictable nature of megafire means that the number of sites that are burned and unburned will be highly variable across monitoring programs. Wood (2022) use simulations and empirical data to assess the power to detect species' responses to megafire that burn a subset of sites belonging to a longer-term monitoring program. They show that landscape-scale monitoring could detect crude changes in populations, but typically lack power to ascertain the form of the post-fire trajectory (Wood, 2022). Of course, power to detect such responses was enhanced by having many sites, underscoring the importance of large, long-term monitoring networks in fire-prone landscapes.

A prime objective in the immediate aftermath of a megafire is to undertake rapid surveys that assess the immediate impacts on biodiversity (Southwell et al., 2022). Ultimately, these reconnaissance missions aim to search for signs of life in the firegrounds and to help deliver a rapid understanding of the potential impacts on species or communities, which can guide management interventions. Such surveys are typically undertaken at short notice, in reaction to a fire event with no "rule book" to follow. Southwell et al. (2022) provide guidelines for best practice reconnaissance surveys following megafire that maximise the chance of detecting focal species, minimise the costs of surveys, and draw upon—wherever possible—existing monitoring programmes. They highlight that species distribution models can be paired with fire severity maps to prioritise areas for rapid reconnaissance; the importance of considering detectability and the statistical power of surveys; and the capacity to value-add to on-ground surveys by concurrently measuring potential threats.

4 | IDENTIFYING POTENTIALLY IMPACTED SPECIES

A pressing need during and after megafires are to rapidly identify species most likely in need of conservation investment. Three approaches are described in this Special Issue, each relating to the Australian megafires (two at a continental scale, and one at a regional scale).

Legge et al. (2022) outlines a method for identifying potentially impacted animal species after megafires, which combines the overlap between a species' geographic range and the fire event, and the pre-fire imperilment of a species, indicated by its conservation status. The intersection of these two measures creates a matrix: critically endangered species with a high proportion (>80%) of their geographic range within the fire footprint receive the highest score,

while unlisted species with a small proportion of their habitat within the fire footprint (e.g., <10%) receive the lowest score. This approach provides a rapid means of identifying potentially imperilled species with just two inputs. However, species have different relationships with fire (Topp et al., 2022): some species may be minimally affected, others may be substantially affected. To account for this, Legge et al. (2022) consider traits of animals that could confer vulnerability to both fire and the post-fire landscape. They use these traits to decide on the inclusion or exclusion species with intermediate risk scores.

Gallagher et al. (2021) demonstrate another continental approach to prioritising species in need of urgent conservation interventions, focussing on plants. In addition to the amount of a species range that overlaps with the Australian megafires, Gallaher et al. (2021) consider the cumulative effects of past fires, and how they might interact with the megafires to further imperil species, depending on their traits (e.g., obligate seeding species vulnerability to repeated fires in short succession). In doing so, they identified nearly 600 species at risk of decline or extinction from the Australian megafires. Given that species' responses to fire depend not only on the most recent fire, but on the cumulative fire history of an area (i.e., the fire regime; Gill, 1975), some consideration of fire history is warranted for other taxa as well.

Finally, Geary et al. (2022) demonstrate prioritisation at the regional level (Victoria, Australia). Here, distribution models of ~4,200 plants and animals were used to rapidly assess fire overlap while the fires were still burning. Geary et al. (2022) provide a more nuanced measure of fire overlap, drawing on their models to weigh proportional fire overlap by habitat suitability. Geary et al. (2022) used 40% of fire overlap as their threshold for consideration as a priority species, which they then vetted further using expert advice and consideration of traits that could mediate a species response to fire. Geary et al. (2022) also highlight the utility of spatial conservation action planning (Thomson et al., 2020) to help guide decisions on where and when to act to derive the most cost-effective conservation benefit (i.e., minimising species decline). If the goal of prioritisation following a megafire is to meet an objective (e.g., minimising the probability of extinction) within a given budget, then a move towards prioritising actions will be needed at all levels (see Game et al., 2013).

While the attention and emotions of the world are captured in the moment by stories of the plights of animals at risk from mega-fires, there is a risk of losing public support if our data do not hold true. It is therefore imperative that these rapid assessment tools are accurate enough to provide a realistic picture of the risks. The three means of identifying vulnerable species each focus on the proportion of a species' range that occurs within the fire footprint. While measuring fire overlap might appear straightforward, Crates et al. (2022) show the importance of high-quality distributional data for assessing the overlap between megafire and species' ranges. Here, simple measures such as Extent of Occurrence or Area of Occupancy tended to underestimate the extent of overlap compared with more detailed measures such as overlap with known, recent breeding locations. These issues are magnified for less well-studied taxa, such as reptiles and invertebrates, due to poor monitoring data for most species, a lack of conservation assessments for described species, and the abundance of undescribed

or cryptic species (Legge et al., 2022). Uncertainty about species' traits and how they mediate responses to fire of varying severities is another area that requires attention if traits continue to be used in such frameworks. As monitoring data accrues, it will be vital to compare the actual impacts of the fires on species with those predicted by these rapid desktop assessments, and to adapt methods, where necessary, to bring on-ground and desktop assessments into closer alignment.

5 | STATE SHIFTS

Among the most concerning impacts of megafire—and of altered fire regimes more generally—is the capacity for fire to induce shifts in ecosystem states across vast areas (Harris et al., 2018; Rammer et al., 2021). Larger, more frequent fires result in shortened fire intervals, leading in some instances to ecological state shifts (Enright et al., 2015). For instance, forests dominated by obligate seeding species face “immaturity risk” when fire intervals are too short for them to reach reproductive maturity between successive fires (Keeley et al., 1999), potentially resulting in their replacement by resprouting species (Nolan et al., 2021). The conversion of dominant canopy species set in motion changes that flow throughout the ecosystem, likely compounded by further changes in fire regimes owing to altered fuel biomass and dryness (Coop et al., 2020; Enright et al., 2015). Via widespread state-shifts—reinforced by positive feedbacks that promote flammability—megafire could be a primary mechanism hastening widespread conversion of vegetation types under climate change.

McColl-Gausden et al. (2022) provide a case study of immaturity risk for the obligate seeding Alpine Ash (*Eucalyptus delegatensis*) in south-eastern Australia, a region that has undergone a substantial increase in fire activity in recent decades (Bowman et al., 2016; Fairman et al., 2015). Alpine ash requires 15–20 years to reach reproductive maturity, so if multiple fires occur within a 20-year window, alpine ash forests can be converted into shrublands (Bassett et al., 2015). Similar state shifts have been described in North America following the loss of obligate-seeding conifers (Coop et al., 2020). McColl-Gausden et al. (2022) use projections of future fire regimes to examine the extent and drivers of immaturity risk across 283,000 hectares of alpine ash forest. They show that over two-thirds of the forest was exposed to immaturity risk, with forests on the margins of the species' geographic range and in drier regions being most at risk. While obligate seeding species were the focus of this study, it is important to recognise that resprouting species are also considered vulnerable to fire-induced state shifts (Nolan et al., 2021).

6 | MEGAFIRE INTERVENTIONS

Although large and intense fires are not new (Bradstock, 2008), the unprecedented size, severity, and frequency of recent megafires have created a perceived need for a suite of conservation interventions aimed specifically at minimising post-fire impacts and promoting recovery of species and communities. Legge et al. (2022) and Geary

et al. (2022) highlight a number of these, including pre-fire extraction of populations with a low likelihood of post-fire survival, provision of artificial refuges (e.g., artificial hollows) or supplementary food to replace resources incinerated by fire, and the control of invasive species that could compound the impacts of fire. Virtually all these interventions have a piecemeal evidence base underpinning their implementation in a post-fire context, and so research is needed to help document their effectiveness. In some instances, action may not be needed, and unnecessary interventions could squander scarce conservation resources. In terms of reversing fire-induced state shifts, some ambitious projects have already been attempted. Bassett et al. (2015) aeriably sowed ~2,000 ha of alpine ash forests that had failed to regenerate after frequent fires in southern Australia, demonstrating that such an intervention could create a cohort of seedlings where interval squeeze has obliterated natural seed stores. The capacity to scale up such efforts from thousands to tens or hundreds of thousands of hectares, and the wisdom of doing so—of attempting to retain an ecological system in an artificial state while the niche of its dominant species disappears—requires careful consideration.

7 | MEGAFIRE ECOLOGY

Megafires have raised new questions for fire ecologists that might require a different way of thinking about fire and biodiversity (Kelly et al., 2020; Nimmo et al., 2021): a new “megafire ecology”. Megafire ecology is focussed on the specific drivers and outcomes of exceptionally large fires on species, communities, and ecosystems. Such large fires, although relatively rare, usually make up the majority of burned area and are ecologically extreme events (Attiwill & Binkley, 2013). One of their defining attributes—their size—means that megafires likely have distinct ecological impacts and may require distinct modes of ecological recovery, for instance, a greater reliance on *in situ* recovery than smaller fires. This could mean that the pace of recovery from megafire is slower for some ecosystem components, relative to smaller fires. The incidence of megafires over time comprises a megafire regime: the interval between megafires, their intensity and severity, are not divorced from the overall fire regime, but might leave a clear ecological signature, comprising a distinctive force shaping species and ecosystems.

Five core areas of research in megafire ecology are summarised below:

1. Identifying the drivers of megafire in search of options for managing fire size, intensity, and severity, including the relative and interacting roles of climate and land use (Khorshidi et al., 2020; Stephens et al., 2014). Of increasing interest is the potential for cultural fire to play a role in diminishing the threat of megafire amidst a warming climate (Dickson-Hoyle et al., 2021; Fletcher et al., 2021).
2. Understanding the effects (both short and long-term) of megafire on populations, species, communities, and ecosystems, including the impact on species' extinction risk and the mechanisms governing recovery, how these are mediated by species' traits (habitat specificity, mobility, fire-avoidance strategies), and how they are influenced by underlying fire regimes.
3. Developing tools to rapidly and accurately identify at-risk species, and to prioritise monitoring and actions that ensure interventions are undertaken when and where they are most effective.
4. Examining the efficacy of actions aimed at limiting decline and hastening recovery following megafire, from species-specific to ecosystem-level interventions.
5. Assessing how megafire reconfigures species interaction networks by transforming the ecological setting in which species interactions and ecological processes take place (Newsome & Spencer, 2022).

There is accruing evidence that the impacts of megafires are far-reaching (Peters et al., 2021; Tang et al., 2021). Very large fires change land surface properties (e.g., albedo, evapotranspiration, roughness) over large areas with the potential to affect regional weather conditions for the post-fire period (Saha et al., 2016). Hence, a holistic understanding of the ecological effects of megafires will require researchers to look far beyond the fire footprint. While political, public, and even scientific interest in megafires is most intense during and immediately after the fire event, the impacts of fires can persist for decades and centuries (Haslem et al., 2011; Nimmo et al., 2012). The 1988 Yellowstone fires provide a case study of lessons that can be learned by tracking an ecosystem's long-term post-fire trajectory (Romme et al., 2016). The megafires that motivated this Special Issue will continue to have their presence felt throughout landscapes in the coming decades and beyond. It is vital that ecologists and land managers continue to monitor how, or if, these ecosystems recover, and the factors that mediate post-fire dynamics. When doing so, it will be important to keep in mind that megafires will not act in isolation, but with indirect effects of climate change, land uses, and invasive species, opening a potentially whole new field in global change biology.

8 | BIO SKETCH

The authors of this manuscript acted as guest editors for the “Fire ecology for the 21st century: conserving biodiversity in the age of megafire” Special Issue and encompass expertise in fire ecology and behaviour from a range of ecosystems across the globe.

ACKNOWLEDGEMENTS

We would like to acknowledge all the authors who contributed to the “Fire ecology for the 21st century: conserving biodiversity in the age of megafire” Special Issue, the reviewers who contributed their considerable time and expertise, and the editorial board of *Diversity and Distributions* for proposing the Special Issue topic. We pay our respects to the Traditional Owners and custodians of the lands on which all research in this Special Issue took place.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING INFORMATION


Australian Research Council : DECRA (DE170101466)

PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/ddi.13482>.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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REFERENCES

- Abram, N. J., Henley, B. J., Gupta, A. S., Lippmann, T. J., Clarke, H., Dowdy, A. J., Sharples, J. J., Nolan, R. H., Zhang, T., Wooster, M. J., Wurtzel, J. B., Meissner, K. J., Pitman, A. J., Ukkola, A. M., Murphy, B. P., Tapper, N. J., & Boer, M. M. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment*, 2(1), 1–17. <https://doi.org/10.1038/s43247-020-00065-8>
- Andersen, A. N. (2021). Faunal responses to fire in Australian tropical savannas: Insights from field experiments and their lessons for conservation management. *Diversity and Distributions*, 27(5), 828–843. <https://doi.org/10.1111/ddi.13198>
- Attwill, P., & Binkley, D. (2013). Exploring the Mega-fire Reality 2011: A Forest Ecology and Management Conference, Florida State University Conference Center, Florida, USA, 14–17 November 2011. *Forest Ecology and Management*, 294, 1–261.
- Banks, S. C., Dujardin, M., McBurney, L., Blair, D., Barker, M., & Lindenmayer, D. B. (2011). Starting points for small mammal population recovery after wildfire: recolonisation or residual populations? *Oikos*, 120(1), 26–37. <https://doi.org/10.1111/j.1600-0706.2010.18765.x>
- Banks, S. C., McBurney, L., Blair, D., Davies, I. D., & Lindenmayer, D. B. (2017). Where do animals come from during post-fire population recovery? Implications for ecological and genetic patterns in post-fire landscapes. *Ecography*, 40(11), 1325–1338. <https://doi.org/10.1111/ecog.02251>
- Barley, S. C., & Meeuwig, J. J. (2017). The power and the pitfalls of large-scale, unreplicated natural experiments. *Ecosystems*, 20(2), 331–339. <https://doi.org/10.1007/s10021-016-0028-5>
- Bassett, O. D., Prior, L. D., Slijkerman, C. M., Jamieson, D., & Bowman, D. M. (2015). Aerial sowing stopped the loss of alpine ash (*Eucalyptus delegatensis*) forests burnt by three short-interval fires in the Alpine National Park, Victoria, Australia. *Forest Ecology and Management*, 342, 39–48. <https://doi.org/10.1016/j.foreco.2015.01.008>
- Boer, M. M., de Dios, V. R., & Bradstock, R. A. (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10(3), 171–172. <https://doi.org/10.1038/s41558-020-0716-1>
- Bowman, D. M., Perry, G. L., Higgins, S. I., Johnson, C. N., Fuhlendorf, S. D., & Murphy, B. P. (2016). Pyrodiversity is the coupling of biodiversity and fire regimes in food webs. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1696), 20150169. <https://doi.org/10.1098/rstb.2015.0169>
- Bowman, D. M., Williamson, G. J., Prior, L. D., & Murphy, B. P. (2016). The relative importance of intrinsic and extrinsic factors in the decline of obligate seeder forests. *Global Ecology and Biogeography*, 25(10), 1166–1172. <https://doi.org/10.1111/geb.12484>
- Bradstock, R. A. (2008). Effects of large fires on biodiversity in south-eastern Australia: disaster or template for diversity? *International Journal of Wildland Fire*, 17(6), 809–822. <https://doi.org/10.1071/WF07153>
- Calhoun, K. L., Chapman, M., Tubbesing, C., McInturff, A., Gaynor, K. M., Van Scoyoc, A., & Brashares, J. (2022). Spatial overlap of wild-fire and biodiversity in California highlights gap in non-conifer fire research and management. *Diversity and Distributions*, 28(3), 529–541. <https://doi.org/10.1111/ddi.13394>
- Collins, L., Bradstock, R. A., Clarke, H., Clarke, M. F., Nolan, R. H., & Penman, T. D. (2021). The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters*, 16(4), 44029. <https://doi.org/10.1088/1748-9326/abeb9e>
- Connell, J., Hall, M. A., Nimmo, D. G., Watson, S. J., & Clarke, M. F. (2022). Fire, drought and flooding rains: The effect of climatic extremes on

- bird species' responses to time since fire. *Diversity and Distributions*, 28(3), 417–438. <https://doi.org/10.1111/ddi.13287>
- Coop, J. D., Parks, S. A., Stevens-Rumann, C. S., Crausbay, S. D., Higuera, P. E., Hurteau, M. D., & Collins, B. M. (2020). Wildfire-driven forest conversion in western North American landscapes. *BioScience*, 70(8), 659–673. <https://doi.org/10.1093/biosci/biaa061>
- Crates, R., Rayner, L., Stojanovic, D., Scheele, B. C., Roff, A., MacKenzie, J., & Heinsohn, R. (2022). Poor-quality monitoring data underestimate the impact of Australia's megafires on a critically endangered songbird. *Diversity and Distributions*, 28(3), 506–514. <https://doi.org/10.1111/ddi.13385>
- Dickson-Hoyle, S., Ignace, R. E., Ignace, M. B., Hagerman, S. M., Daniels, L. D., & Copes-Gerbitz, K. (2021). Walking on two legs: a pathway of Indigenous restoration and reconciliation in fire-adapted landscapes. *Restoration Ecology*, <https://doi.org/10.1111/rec.13566>
- Duane, A., Castellnou, M., & Brotons, L. (2021). Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change*, 165(3), 1–21. <https://doi.org/10.1007/s10584-021-03066-4>
- Ellis, T. M., Bowman, D. M. J. S., Jain, P., Flannigan, M. D., & Williamson, G. J. (2021). Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global Change Biology*, 28(4), 1544–1559. <https://doi.org/10.1111/gcb.16006>
- Enright, N. J., Fontaine, J. B., Bowman, D. M., Bradstock, R. A., & Williams, R. J. (2015). Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment*, 13(5), 265–272. <https://doi.org/10.1890/140231>
- Fairman, T. A., Nitschke, C. R., & Bennett, L. T. (2015). Too much, too soon? A review of the effects of increasing wildfire frequency on tree mortality and regeneration in temperate eucalypt forests. *International Journal of Wildland Fire*, 25(8), 831–848. <https://doi.org/10.1071/WF15010>
- Fletcher, M.-S., Romano, A., Connor, S., Mariani, M., & Maezumi, S. Y. (2021). Catastrophic Bushfires, Indigenous Fire Knowledge and Reframing Science in Southeast Australia. *Fire*, 4(3), 61. <https://doi.org/10.3390/fire4030061>
- Furnas, B. J., Goldstein, B. R., & Figura, P. J. (2022). Intermediate fire severity diversity promotes richness of forest carnivores in California. *Diversity and Distributions*, 28(3), 493–505. <https://doi.org/10.1111/ddi.13374>
- Gallagher, R. V., Allen, S., Mackenzie, B. D., Yates, C. J., Gosper, C. R., Keith, D. A., Merow, C., White, M. D., Wenk, E., Maitner, B. S., He, K., Adams, V. M., & Auld, T. D. (2021). High fire frequency and the impact of the 2019–2020 megafires on Australian plant diversity. *Diversity and Distributions*, 27(7), 1166–1179. <https://doi.org/10.1111/ddi.13265>
- Game, E. T., Kareiva, P., & Possingham, H. P. (2013). Six common mistakes in conservation priority setting. *Conservation Biology*, 27(3), 480–485. <https://doi.org/10.1111/cobi.12051>
- Geary, W. L., Buchan, A., Allen, T., Attard, D., Bruce, M. J., Collins, L., Ecker, T. E., Fairman, T. A., Hollings, T., Loeffler, E., Muscatello, A., Parkes, D., Thomson, J., White, M., & Kelly, E. (2022). Responding to the biodiversity impacts of a megafire: A case study from south-eastern Australia's Black Summer. *Diversity and Distributions*, 28(3), 463–478. <https://doi.org/10.1111/ddi.13292>
- Gill, A. M. (1975). Fire and the Australian flora: a review. *Australian Forestry*, 38(1), 4–25. <https://doi.org/10.1080/00049158.1975.10675618>
- Greenwood, L., Bliege Bird, R., & Nimmo, D. (2021). Indigenous burning shapes the structure of visible and invisible fire mosaics. *Landscape Ecology*, 1–17. <https://doi.org/10.1007/s10980-021-01373-w>
- Hale, S., Mendoza, L., Yeatman, T., Cooke, R., Doherty, T., Nimmo, D., & White, J. G. (2022). Evidence that post-fire recovery of small mammals occurs primarily via in situ survival. *Diversity and Distributions*, 28(3), 404–416. <https://doi.org/10.1111/ddi.13283>
- Harris, R. M., Beaumont, L. J., Vance, T. R., Tozer, C. R., Remenyi, T. A., Perkins-Kirkpatrick, S. E., Mitchell, P. J., Nicotra, A. B., McGregor, S., Andrew, N. R., Letnic, M., Kearney, M. R., Wernberg, T., Hutley, L. B., Chambers, L. E., Fletcher, M.-S., Keatley, M. R., Woodward, C. A., Williamson, G., ... Bowman, D. M. J. S. (2018). Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, 8(7), 579–587. <https://doi.org/10.1038/s41558-018-0187-9>
- Haslem, A., Kelly, L. T., Nimmo, D. G., Watson, S. J., Kenny, S. A., Taylor, R. S., & Clarke, M. F. (2011). Habitat or fuel? Implications of long-term, post-fire dynamics for the development of key resources for fauna and fire. *Journal of Applied Ecology*, 48(1), 247–256. <https://doi.org/10.1111/j.1365-2664.2010.01906.x>
- Hempson, G. P., Parr, C. L., Archibald, S., Anderson, T. M., Mustaphi, C. J. C., Dobson, A. P., & Beale, C. M. (2018). Continent-level drivers of African pyrodiversity. *Ecography*, 41(6), 889–899. <https://doi.org/10.1111/ecog.03109>
- Jain, P., Castellanos-Acuna, D., Coogan, S. C., Abatzoglou, J. T., & Flannigan, M. D. (2021). Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nature Climate Change*, 1–8. <https://doi.org/10.1038/s41558-021-01224-1>
- Jolly, C. J., Dickman, C. R., Doherty, T. S., Eeden, L. M., Geary, W. L., Legge, S. M., Woinarski, J. C. Z., & Nimmo, D. G. (2022). Animal mortality during fire. *Global Change Biology*, <https://doi.org/10.1111/gcb.16044>
- Jones, G. M., Gutiérrez, R., Tempel, D. J., Whitmore, S. A., Berigan, W. J., & Peery, M. Z. (2016). Megafires: an emerging threat to old-forest species. *Frontiers in Ecology and the Environment*, 14(6), 300–306. <https://doi.org/10.1002/fee.1298>
- Jones, G. M., & Tingley, M. W. (2022). Pyrodiversity and biodiversity: a history, synthesis, and outlook. *Diversity and Distributions*, 28(3), 386–403. <https://doi.org/10.1111/ddi.13280>
- Keeley, J. E., Ne'eman, G., & Fotheringham, C. (1999). Immaturity risk in a fire-dependent pine. *Journal of Mediterranean Ecology*, 1(8), 41–48.
- Keeley, J. E., & Syphard, A. D. (2021). Large California wildfires: 2020 fires in historical context. *Fire Ecology*, 17(1), 1–11. <https://doi.org/10.1186/s42408-021-00110-7>
- Keith, D. A. (2021). Transcending the disaster paradigm: Understanding persistence of animal populations in fire-prone environments. *Global Change Biology*, 28(2), 341–342. <https://doi.org/10.1111/gcb.15925>
- Kelly, L. T., Brotons, L., & McCarthy, M. A. (2016). Putting pyrodiversity to work for animal conservation. *Conservation Biology*, 31(4), 952–955. <https://doi.org/10.1111/cobi.12861>
- Kelly, L. T., Giljohann, K. M., Duane, A., Aquilué, N., Archibald, S., Batllori, E., Bennett, A. F., Buckland, S. T., Canelles, Q., Clarke, M. F., Fortin, M.-J., Hermoso, V., Herrando, S., Keane, R. E., Lake, F. K., McCarthy, M. A., Morán-Ordóñez, A., Parr, C. L., Pausas, J. G., ... Brotons, L. (2020). Fire and biodiversity in the Anthropocene. *Science*, 370(6519). <https://doi.org/10.1126/science.abb0355>
- Khorshidi, M. S., Dennison, P. E., Nikoo, M. R., AghaKouchak, A., Luce, C. H., & Sadegh, M. (2020). Increasing concurrence of wildfire drivers tripled megafire critical danger days in Southern California between 1982 and 2018. *Environmental Research Letters*, 15(10), 104002. <https://doi.org/10.1088/1748-9326/abae9e>
- Legge, S., Woinarski, J. C. Z., Scheele, B. C., Garnett, S. T., Lintermans, M., Nimmo, D. G., Whiterod, N. S., Southwell, D. M., Ehmke, G., Buchan, A., Gray, J., Metcalfe, D. J., Page, M., Rumpff, L., Leeuwen, S., Williams, D., Ah Yong, S. T., Chapple, D. G., Cowan, M., ... Tingley, R. (2022). Rapid assessment of the biodiversity impacts of the 2019–2020 Australian megafires to guide urgent management intervention and recovery and lessons for other regions. *Diversity and Distributions*, 28(3), 571–591. <https://doi.org/10.1111/ddi.13428>

- Martin, R., & Sapsis, D. (1992). Fires as agents of biodiversity: pyrodiversity promotes biodiversity. In H. M. Kerner (Ed.), (pp. 150–157). *Paper presented at the Proceedings: symposium on biodiversity of northwestern California*. Center of. Wildland Resources Report
- McCull-Gausden, S. C., Bennett, L. T., Ababei, D. A., Clarke, H. G., & Penman, T. D. (2022). Future fire regimes increase risks to obligate-seeder forests. *Diversity and Distributions*, 28(3), 542–558. <https://doi.org/10.1111/ddi.13417>
- Miller, J. E., Weill, A. M., & Villella, J. (2022). Epiphytic macrolichen communities take decades to recover after high-severity wildfire in chaparral shrublands. *Diversity and Distributions*, 28(3), 454–462. <https://doi.org/10.1111/ddi.13295>
- Newsome, T. M., & Spencer, E. E. (2022). Megafires attract avian scavenging but carcasses still persist. *Diversity and Distributions*, 28(3), 515–528. <https://doi.org/10.1111/ddi.13390>
- Nimmo, D. G., Avitabile, S., Banks, S. C., Bliege Bird, R., Callister, K., Clarke, M. F., Dickman, C. R., Doherty, T. S., Driscoll, D. A., Greenville, A. C., Haslem, A., Kelly, L. T., Kenny, S. A., Lahoz-Monfort, J. J., Lee, C., Leonard, S., Moore, H., Newsome, T. M., Parr, C. L., ... Bennett, A. F. (2019). Animal movements in fire-prone landscapes. *Biological Reviews*, 94(3), 981–998. <https://doi.org/10.1111/brv.12486>
- Nimmo, D. G., Carthey, A. J., Jolly, C. J., & Blumstein, D. T. (2021). Welcome to the Pyrocene: Animal survival in the age of megafire. *Global Change Biology*, 27(22), 5684–5693. <https://doi.org/10.1111/gcb.15834>
- Nimmo, D. G., Kelly, L. T., Spence-Bailey, L. M., Watson, S. J., Haslem, A., White, J. G., Clarke, M. F., & Bennett, A. F. (2012). Predicting the century-long post-fire responses of reptiles. *Global Ecology and Biogeography*, 21(11), 1062–1073. <https://doi.org/10.1111/j.1466-8238.2011.00747.x>
- Nolan, R. H., Collins, L., Leigh, A., Ooi, M. K., Curran, T. J., Fairman, T. A., Resco de Dios, V., & Bradstock, R. (2021). Limits to post-fire vegetation recovery under climate change. *Plant, Cell & Environment*, 44(11), 3471–3489. <https://doi.org/10.1111/pce.14176>
- Parr, C. L., & Andersen, A. N. (2006). Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. *Conservation Biology*, 20(6), 1610–1619. <https://doi.org/10.1111/j.1523-1739.2006.00492.x>
- Peters, A., Hume, S., Raidal, S., Crawley, L., & Gowland, D. (2021). Mortality Associated with Bushfire Smoke Inhalation in a Captive Population of the Smoky Mouse (*Pseudomys fumeus*), a Threatened Australian Rodent. *Journal of Wildlife Diseases*, 57(1), 199–204. <https://doi.org/10.7589/JWD-D-20-00026>
- Pyne, S. (2020). From Pleistocene to Pyrocene: fire replaces ice. *Earth's Future*, 8(11), e2020EF001722. <https://doi.org/10.1029/2020EF001722>
- Rainsford, F. W., Kelly, L. T., Leonard, S. W., & Bennett, A. F. (2022). Fire and functional traits: Using functional groups of birds and plants to guide management in a fire-prone, heathy woodland ecosystem. *Diversity and Distributions*, 28(3), 372–385. <https://doi.org/10.1111/ddi.13278>
- Rammer, W., Braziunas, K. H., Hansen, W. D., Ratajczak, Z., Westerling, A. L., Turner, M. G., & Seidl, R. (2021). Widespread regeneration failure in forests of Greater Yellowstone under scenarios of future climate and fire. *Global Change Biology*, 27(18), 4339–4351. <https://doi.org/10.1111/gcb.15726>
- Romme, W. H., Whitby, T. G., Tinker, D. B., & Turner, M. G. (2016). Deterministic and stochastic processes lead to divergence in plant communities 25 years after the 1988 Yellowstone fires. *Ecological Monographs*, 86(3), 327–351.
- Saha, M. V., Scanlon, T. M., & D'Odorico, P. (2016). Suppression of rainfall by fires in African drylands. *Geophysical Research Letters*, 43(16), 8527–8533. <https://doi.org/10.1002/2016GL069855>
- Southwell, D., Legge, S., Woinarski, J., Lindenmayer, D., Lavery, T., & Wintle, B. (2022). Design considerations for rapid biodiversity reconnaissance surveys and long-term monitoring to assess the impact of wildfire. *Diversity and Distributions*, 28(3), 559–570. <https://doi.org/10.1111/ddi.13427>
- Steel, Z. L., Fogg, A. M., Burnett, R., Roberts, L. J., & Safford, H. D. (2022). When bigger isn't better—Implications of large high-severity wildfire patches for avian diversity and community composition. *Diversity and Distributions*, 28(3), 439–453. <https://doi.org/10.1111/ddi.13281>
- Stephens, S. L., Burrows, N., Buyantuyev, A., Gray, R. W., Keane, R. E., Kubian, R., Liu, S., Seijo, F., Shu, L., Tolhurst, K. G., & van Wagtenonk, J. W. (2014). Temperate and boreal forest megafires: Characteristics and challenges. *Frontiers in Ecology and the Environment*, 12(2), 115–122. <https://doi.org/10.1890/120332>
- Tang, W., Llort, J., Weis, J., Perron, M. M., Basart, S., Li, Z., Sathyendranath, S., Jackson, T., Rodriguez, E. S., Proemse, B. C., Bowie, A. R., Schallenberg, C., Strutton, P. G., & Matear, R., Proemse, B. C. (2021). Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature*, 597(7876), 370–375.
- Taylor, R. S., Watson, S. J., Nimmo, D. G., Kelly, L. T., Bennett, A. F., & Clarke, M. F. (2012). Landscape-scale effects of fire on bird assemblages: does pyrodiversity beget biodiversity? *Diversity and Distributions*, 18(5), 519–529. <https://doi.org/10.1111/j.1472-4642.2011.00842.x>
- Thomson, J., Regan, T. J., Hollings, T., Amos, N., Geary, W. L., Parkes, D., Hauser, C. E., White, M. (2020). Spatial conservation action planning in heterogeneous landscapes. *Biological Conservation*, 250, 108735.
- Topp, E. N., Tschardt, T., & Loos, J. (2022). Fire and landscape context shape plant and butterfly diversity in a South African shrubland. *Diversity and Distributions*, 28(3), 357–371. <https://doi.org/10.1111/ddi.13257>
- Van Eeden, L., Nimmo, D., Mahony, M., Herman, K., Ehmke, G., Driessen, J., O'Connor, J., Bino, G., Taylor, M., & Dickman, C. R. (2020). *Impacts of the unprecedented 2019–2020 Bushfires on Australian animals*. Report Prepare for WWF-Australia.
- Ward, M., Tulloch, A. I., Radford, J. Q., Williams, B. A., Reside, A. E., Macdonald, S. L., Mayfield, H. J., Maron, M., Possingham, H. P., Vine, S. J., O'Connor, J. L., Massingham, E. J., Greenville, A. C., Woinarski, J. C. Z., Garnett, S. T., Lintermans, M., Scheele, B. C., Carwardine, J., Nimmo, D. G., Lindenmayer, D. B., Kooyman, R. M., Simmonds, J. S., Sonter, L. J., & Watson, J. E. M. (2020). Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution*, 4(10), 1321–1326. <https://doi.org/10.1038/s41559-020-1251-1>
- Wintle, B. A., Legge, S., & Woinarski, J. C. (2020). After the megafires: What next for Australian wildlife? *Trends in Ecology & Evolution*, 35(9), 753–757. <https://doi.org/10.1016/j.tree.2020.06.009>
- Wood, C. M. (2022). Optimizing landscape-scale monitoring programmes to detect the effects of megafires. *Diversity and Distributions*, 28(3), 479–492. <https://doi.org/10.1111/ddi.13308>
- Wu, C., Venevsky, S., Sitch, S., Mercado, L. M., Huntingford, C., & Staver, A. C. (2021). Historical and future global burned area with changing climate and human demography. *One Earth*, 4(4), 517–530. <https://doi.org/10.1016/j.oneear.2021.03.002>