

## The impacts of the 2019–20 wildfires on Australian fungi

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### Summary

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#### *Context and challenges*

- Fungi are megadiverse but poorly documented in Australia and worldwide.
- Major trophic modes are parasitism, saprotrophism and mutualism (e.g. lichens and mycorrhizas).
- Fungi are functionally important in ecosystems, particularly through mutualistic interactions with other biota and as decomposers.
- Many fungi have wide distributions which means that specific knowledge of life history and threats is usually required to assess conservation status.
- Few fungi are formally listed as threatened under Australian legislation.
- Some fungi are adapted to fire through production of heat-resistant spores or underground resting stages.
- Recent metabarcoding studies on fungal communities have detected positive and negative effects of fire on the presence and abundance of different guilds of fungi.

#### *Main findings*

- Based on spatial analysis of distributional records, we found that:
  - Only half the fungi known from Australia are represented in accessible distribution databases.
  - Most species with some accessible distribution data are represented by one or few records.
- In relation to the 2019–20 wildfires, we found that:
  - At least part of the range of 3523 species of fungi was burnt.
  - 177 species had at least 50% of their range burnt in fires of any severity.

- ▶ 188 species had at least 20% of their range burnt by fires of high severity.
- ▶ 59 species had all of their known range burnt by fires of high severity. However, they all had only one or two unique records, so their fire overlap values are of low confidence.
- There will also be numerous undescribed species of fungi potentially affected by the 2019–20 wildfires.
- The species identified as having high overlap with fire are a priority for assessment of traits and threat status.
- Future monitoring will benefit from combining single-species approaches with whole-community sampling using metabarcoding.

## Introduction

### What are fungi?

Kingdom *Fungi* is one of the major radiations in the tree of life. Fungi can be defined simply as organisms that have hyphae and reproduce by spores, although there are exceptions, such as the single-celled yeasts. Hyphae are branching filaments forming a network called a mycelium.

The most familiar fungi are macrofungi with readily visible sporing bodies, such as mushrooms, puffballs, lichens and coral fungi. However, most fungi are microfungi, not readily visible apart from via their symptoms, such as for leaf-spotting fungi. Spores are microscopic and produced sexually and/or asexually in large numbers, often with capacity to travel long distances. The feeding part of the fungus, the mycelium, may be short-lived on ephemeral substrates, or persist for long periods in soil, wood or other substantial substrates. Spore production can be directly on the mycelium or on specialised sporing bodies (such as mushrooms). Sporing bodies can appear annually, often sporadically (as with mushrooms), or may be long-lived (such as the persistent sporing bodies of many bracket fungi).

Fungi are megadiverse but extremely under-documented. There are ~15 000 species already recorded from Australia, from an estimate of between 50 000 and 250 000 expected species (Chapman 2009). Globally, fungal diversity is estimated at between 2.2 and 3.8 million species (Hawksworth and Lücking 2017). Fungi have significant economic impacts that can be negative through animal, human and plant disease, and positive as sources of biologically active compounds (e.g. antibiotics like penicillin) and through the key roles they play in natural environments, as components of food webs, carbon sinks, and symbioses.

Fungi are heterotrophs, requiring carbon from other sources. Key to understanding the role of fungi in ecosystems is appreciation of the diversity of ways in which fungi obtain and share nutrients. The main trophic roles are (1) decomposition (saprotrophism) of a wide range of organic compounds, including those in woody substrates, such as lignin; (2) parasitism of animals, fungi and plants; and (3) mutualisms – the most important of which are mycorrhizas (associations of plant roots and fungi) and lichens (stable associations between fungi and photosynthetic algae or cyanobacteria).

Due to the variety of trophic roles, most species of animals and plants interact with fungi in one way or other. Examples of key ecosystem processes that involve fungi are (1)

biotic soil crusts (of which lichens are a major component), stabilising soil and affecting seed germination, and (2) mycorrhizas of canopy-dominant trees and shrubs, including *Allocasuarina*, *Eucalyptus* and *Nothofagus*, which together cover > 77% of native forest area in Australia (SOFR 2018). An example of the complexity of interactions is the diversity of sequestrate (truffle-like) fungi – many forming mycorrhizal partnerships with forest trees and other plants – the underground sporing bodies of which are consumed by mammals, many of which are threatened.

### Conservation status

Sixty species of fungi are formally listed as threatened or rare under state legislation for New South Wales (nine), Tasmania (28, all lichens), Victoria (eight) and Western Australia (15, all as 'Priority taxa'). Sixteen species of Australian fungi are in the IUCN Red List of Threatened Species, assessed as Critically Endangered, Endangered, Vulnerable or Near Threatened. No fungi are listed as threatened under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*, although several fungi are listed as threatening processes!

The low number of formally threat-listed fungi reflects the paucity of assessments of conservation status rather than lack of threatened species. There is a lack of experts with resources to make the nominations, so nominations are in part community driven and have mostly been *ad hoc* rather than arising from systematic assessment. Few of the fungi identified as threatened in Australia are under active survey or management.

Among other biota, short-range endemics are often among the first species recognised as threatened, due to low extent of occurrence and/or area of occupancy. However, there are few proven short-range endemics among Australian fungi (May 2002). Therefore, for fungi to be listed as threatened generally requires specific knowledge of declines (usually not possible given lack of baseline monitoring), population estimates (technically difficult) or specific threats.

Threats identified for fungi include destruction of habitat and climate change. For obligate symbionts, threats to partner species have been used to identify threats to the fungus, such as for *Cyttaria septentrionalis*, a parasite restricted to Antarctic beech (*Nothofagus moorei*) (itself globally assessed as Vulnerable).

### Fungi and fire

Fire affects soil fungal communities directly (fire-induced mortality) or indirectly through plant–soil–microbe interactions (Wardle *et al.* 2004). High-severity wildfire can heat soils to > 500°C, resulting in the combustion of soil organic matter and leaf litter, volatilisation of soil nutrients and increases in soil pH (Certini 2005; Chapter 5). Changes in soil properties, including pH, manganese, magnesium, phosphorus and nitrate, represent some of the potential mechanisms through which fire may alter microbial communities indirectly (Bowd 2020).

McMullan-Fisher *et al.* (2011) reviewed fire and fungi in Australia, concluding that fire effects are variable in space and in relation to taxonomic and trophic groups of fungi. In the first few years after fire there is a flush of fire-adapted fungi – regenerating from sclerotia, the storage bodies formed by genera such as *Laccocephalum* (e.g. native bread, stonemaker), or from heat-resistant spores. There are also fungi that appear to prefer long-unburnt vegetation – for example, the critically endangered *Hypocreopsis amplexens*, found in long-unburnt stands of heathy woodland, and *Roccellinastrum flavescens*, a lichen found exclusively on leaves of pencil pine (*Arthrotaxis cupressoides*) (McMullan-Fisher *et al.* 2011).

The fire regime, in terms of fire intensity and frequency, affects the dynamics of fungal communities (McMullan-Fisher *et al.* 2011; Rincón *et al.* 2014; Egidi *et al.* 2016; Bowd *et al.* 2021). For instance, crown-fire-induced tree mortality can have more severe impacts on ectomycorrhizal and litter-associated fungi than ground-fire-induced losses in soil organic matter (Pérez-Izquierdo *et al.* 2021). The post-fire flush of fungi can be a confounding factor in studies of fire effects, depending on the time since fire across study sites. McMullan-Fisher *et al.* (2011) noted there were few studies that tested the effect of different fire regimes; the studies often lacked replication and they did not yield consistent results.

Ecosystem recovery following fire has dependencies on the resilience of soil fungal communities and maintenance of their interactions with host plants and animal dispersers (Dove and Hart 2017). After fire, fungi have important roles in soil stabilisation and those that produce sporing bodies early in the post-fire succession are often mycorrhizal and support seedling establishment. Sequestrate fungi provide vital food resources for mammals post-fire, as evidenced by frequent diggings. Such diggings help reduce fire frequency and intensity by breaking up hydrophobic layers at the soil surface and improving soil aeration and water penetration (Palmer *et al.* 2020). Some sequestrate fungi appear to produce sporing bodies in greater abundance after fire, but the degree to which fire stimulates sporing body production is unclear, and may vary across ecosystems and fungal lineages.

The persistence of fungal communities post-fire is contingent on species-specific ecological and physiological tolerances and the presence of heat-resistant mycelia and spore banks that allow them to withstand the direct impacts of wildfire (Kurth *et al.* 2013; Glassman *et al.* 2016). Post-fire environments may select for specific taxa including some that thrive due to a lack of competition and the creation of new niches, such as decomposing fire-killed mycelium or fallen trees (Warcup 1990; Rincón *et al.* 2014). In contrast, less fire-tolerant species, including some ectomycorrhizal (ECM) species that specialise in nitrogen uptake from organic sources, may decline after fire for up to a decade (Treseder *et al.* 2004; Pérez-Izquierdo *et al.* 2021). Aside from fire-induced mortality, fire can negatively affect ECM fungal diversity by reducing the diversity and abundance of ECM host trees, such as fire-sensitive *Nothofagus* species, as well as fungal consumers, particularly mammals, that are vital for spore dispersal (Dundas *et al.* 2018).

## Recent research on the effect of fire on soil fungal communities

Recently, molecular-based approaches using DNA metabarcoding of environmental samples (e.g. soil, roots, mammal scats) have opened the door for diversity assessment of microbial communities affected by fire. Studies in Australia have focused on wet forests, investigating both logging and fire. In Victoria, Bowd *et al.* (2021) found fire and logging had negative effects on symbiotic fungi, mediated by changes in soil properties and plant communities. In contrast, they reported an increase in saprotrophic fungi with multiple fires. Similarly in Tasmania, Ammitzbohl *et al.* (2021) reported that logging and high-severity burning reduced fungal biomass including for some symbionts, but had a positive influence on saprotrophs. They suggested that a range of low to moderate burns contribute to habitat diversity and the persistence of diverse soil microbial communities.

## Purpose of this chapter

In this chapter we assess impacts of the 2019–20 wildfires on Australian fungi. We make recommendations arising from the present analysis as well as general recommendations

about enhancements to data infrastructure and further research to improve the knowledge base upon which informed management decisions can be made.

Using the pipeline of Hao *et al.* (2021), we created a cleaned and de-duplicated dataset (accessible at <https://doi.org/10.5281/zenodo.6324422>) on data from the following repositories (downloaded 16 September 2021): (1) Atlas of Living Australia (ALA), (2) Global Biodiversity Information Facility, (3) Fungimap, (4) MycoPortal and (5) iNaturalist. The pipeline discarded records not in native vegetation. The > 1 million records based on environmental DNA from the ALA (a quarter of which are identified to species level) were excluded due to questionable identification accuracy. The final dataset contained records identified to species for Kingdom Fungi (i.e. excluding fungi-like members of other kingdoms).

For the fire overlap analysis, we replicated the methods of Marsh *et al.* (2021; Chapter 11) as applied to invertebrates except that in preparing data: (1) the coordinate uncertainty cut off was > 5 km, although records lacking coordinate uncertainty were retained, (2) specimen and observation data were included (the latter predominantly from Fungimap and iNaturalist, and considered adequate in relation to identifications), and (3) we did not apply a date cut-off, as a significant proportion of data was collected < 1990 or had no date information (33%).

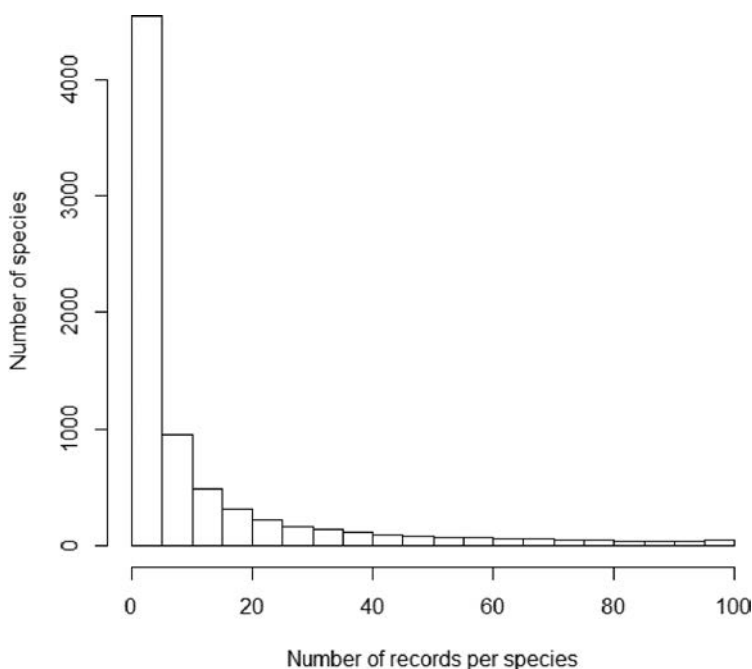
The fire overlap analysis was carried out for the Preliminary Analysis Area (PAA) (see Chapter 1). Overlap with fire was calculated using the GEEBAM fire layer (Department of Agriculture Water and the Environment 2020) at 250 m resolution, which includes classes of severity: (1) no data, (2) unburnt, (3) low and moderate, (4) high, and (5) very high. The fire severity layer was masked so that the overlap analysis only considered fire impacts on native vegetation (see Marsh *et al.* (2021) for details). Total records were converted to unique records across a 2 × 2 km grid. For species with one or two unique records, overlap was in relation to the total number of records (which may be greater than two due to multiple records within the one grid cell). For species with three or more unique records, a range polygon was created using the  $\alpha$  hull method with  $\alpha = 2$  in the ConR package in R (Dauby *et al.* 2017), and overlap with the fire layer was calculated using these polygons. The overlap analyses were carried out for burnt areas (classes: low and moderate, high, or very high) and severely burnt areas (classes: high or very high). Marsh *et al.* (2021) compared analyses treating GEEBAM class 2 (unburnt) as burnt or unburnt, to account for possibility of undetected burning of the understorey. We treated GEEBAM 2 as unburnt. Lists of species with high overlap with fire (i.e. at least 50% overlap with fire or  $\geq 20\%$  overlap with severe fire, corresponding to Tables 10.1 and 10.2) are available for point and polygon data at <https://doi.org/10.5281/zenodo.6324422>.

We acknowledge a range of caveats about the data and analyses, including (1) misapplication of names of Northern Hemisphere taxa, (2) some exotic species may not have been excluded, (3) highly patchy sampling taxonomically and geographically, and (4) the National Species List for fungi is incomplete, meaning data are sometimes attached to different names for the same species or recently described species are omitted.

## Findings

### Characteristics of fungi repository data

The initial cleaned dataset shows that there is a significant lack of readily accessible distribution data for many species of fungi (Fig. 10.1). There are in the order of 15 000 named species of fungi known from Australia but just over half (8251) have any data in the sampled repositories. A few species have been widely recorded, such as the Fungimap target species vermilion grisette (*Amanita xanthocephala*) with almost 4000 records



**Fig. 10.1.** Frequency distribution of the number of records per species for the 7584 species of Australian fungi with at least one record in the sampled repositories. Not shown on this histogram are 667 species that had more than 100 records.

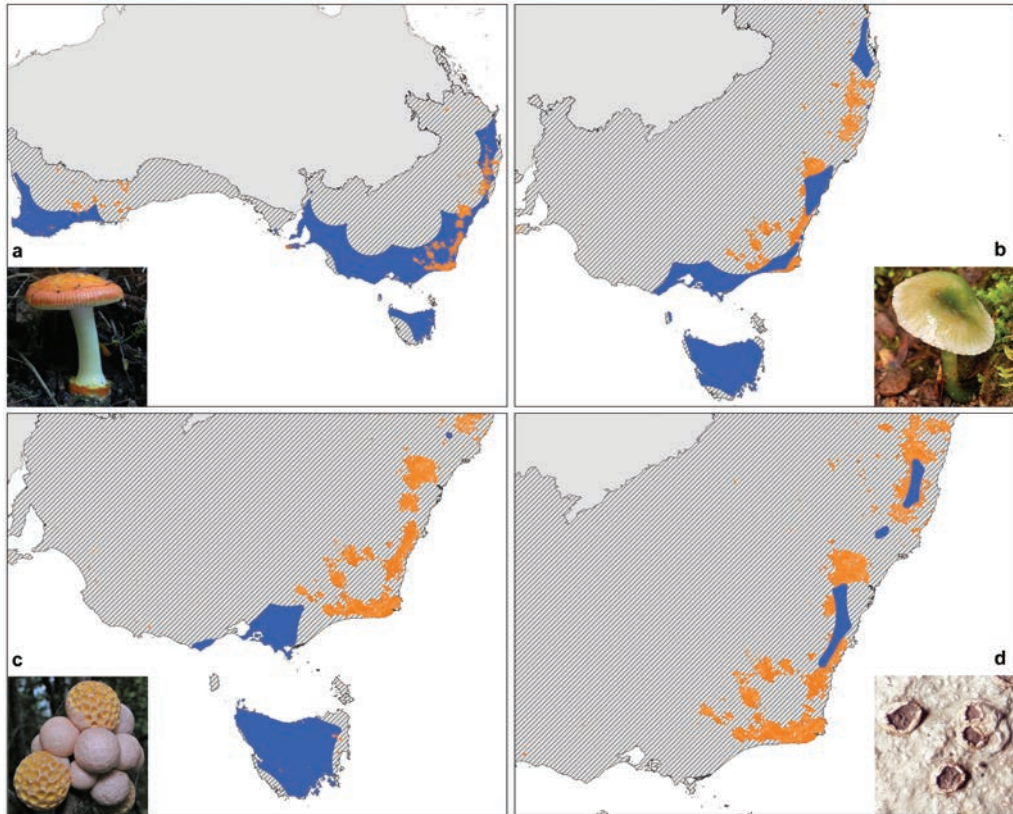
(Fig. 10.2a). However, a quarter of species are represented by just one digitised specimen or observation, and around two-thirds have 10 or fewer records. Although the average number of records is 42, the modal number of records is one. The lack of records is due to a combination of (1) many species are genuinely known only from the type collection and few other collections, and (2) for other species that have more specimens, these are often not fully digitised, particularly the specimens held in non-Australian institutions.

### Fire overlap

Some fungi distributions are displayed against the fire extent in Fig. 10.2, including distributions typical of many species, either spanning eastern and western Australia (Fig. 10.2a) or extending from Tasmania to southern Queensland on the east coast (Fig. 10.2b). In relation to overlap with fire, additional distribution information for species with apparently small distributions may increase or decrease the fire overlap, depending on where the distribution extends with additional data.

Of the 7445 species with at least one data point remaining after data cleaning, 6634 had at least one record within the PAA. Of these, 3523 species had some part of their range overlap with the fire extent (2205 species had an overlap of  $\geq 1\%$ ) and 177 species had at least 50% of their distribution burnt (Table 10.1).

Overlap with fire extent is not the only indication of effect. Fire severity is also an important consideration for impact and recovery. Some 188 species had at least 20% of their distributions burnt by severe fire (Table 10.2). Of these, 59 species had all of their known range burnt. However, all had only one or two unique records, so their fire overlap values are of low confidence.



**Fig. 10.2.** Map of Australia with ranges, as  $\alpha$  hull polygons (in blue), for (a) *Amanita xanthocephala*, (b) *Gliophorus graminicolor*, (c) *Cyttaria gunnii* and (d) *Gintarasia megalophthalma*; demonstrating distributions within the Preliminary Analysis Area (cross-hatched). Extent of the 2019–20 wildfires represented in orange (overlaid in (a) and (c) and underlaid in (b) and (d)). (Photos of fungi: (a) Tom May, (b, c) Paul George, (d) Bill Malcolm)

**Table 10.1.** Tallies of the number of fungal species within the Preliminary Analysis Area with extensive ( $\geq 50\%$ ) overlap with the 2019–20 wildfires.

% distribution overlapping with fire	Number of species		
	Species with 3 or more unique records ( $\alpha$ hull range)	Species with 1 or 2 unique records (point locations)	Total
100	–	112	112
90–99.9	–	–	–
80–89.9	2	–	2
70–79.9	1	–	1
60–69.9	6	5	11
50–59.9	16	35	51
<b>Total with at least 50% overlap with fire</b>	<b>25</b>	<b>152</b>	<b>177</b>

**Table 10.2.** Tallies of the number of fungal species within the Preliminary Analysis Area for which  $\geq 20\%$  of their distribution overlapped with the 2019–20 wildfires that were severe (class high or very high).

% distribution overlapping with severe fire	Number of species		
	Species with 3 or more unique records ( $\alpha$ hull range)	Species with 1 or 2 unique records (point locations)	Total
100	–	59	59
90–99.9	–	–	–
80–89.9	–	–	–
70–79.9	–	–	–
60–69.9	–	5	5
50–59.9	2	20	22
40–49.9	10	–	10
30–39.9	20	2	22
20–29.9	70	–	70
<b>Total with at least 20% overlap with severe fire</b>	<b>102</b>	<b>86</b>	<b>188</b>

When considering morphogroups (groupings of convenience that are similar in overall morphology), many of the species tallied for Tables 10.1 and 10.2 are lichens, with sequestrate fungi and mushrooms the next most prevalent. Among the 86 species that had 50% or greater overlap with severe fire intensity, about half (46) are lichens, 14 are mushrooms, 10 are sequestrate fungi (e.g. *Cortinarius tubercularis*), and the remainder are a mix of microfungi and macrofungi in other morphogroups (such as coral fungi and puffballs).

Among species with  $\geq 20\%$  overlap with severe fire, a few species appear to be rare and/or have specific habitat requirements, suggesting potential for high impact of the 2019–20 wildfires. For example, among lichens, *Sticta hypopsiloides* (two points, 100% overlap with severe fire) is a rare species occurring in montane rainforests in Queensland and *Cresponea ancistrosporelloides* (one point, 100% overlap) is known only from the original collection on rock in sclerophyll forest in Western Australia. Lichens known from more than two sites and with high fire overlap include *Anzia minor* (13 points, 42.3% overlap) and *Hypotrachyna subpustulifera* (three points, 52.1% overlap), both restricted to sandstone sites in New South Wales, and *Gintarasia megalophthalma* (44 points, 25.7% overlap), a species occurring in medium altitude wet forests and rainforests of eastern Australia (Fig. 10.2d).

For many species the distribution as currently known is likely to be incomplete. This is especially so for sequestrate fungi because they form underground sporing bodies and thus require specialised survey techniques. However, three sequestrate species with  $\geq 20\%$  overlap with severe fire are distinctive morphologically and considered uncommon by experts: *Andebbia pachytrix* (30.9% overlap), *Cortinarius argyrionus* (28.1% overlap) and *Leucogaster meridionalis* (27.0% overlap). Among epigeal fungi, some species showing  $\geq 20\%$  overlap with severe fire are known from further collections (not digitised) that indicate a much wider distribution or that there are large areas of potentially suitable habitat between known points (e.g. *Sphaerosoma trispora* and *Galerina lurida*).

None of the 75 species of Australian fungi listed on the IUCN Red List of Threatened Species or under state conservation legislation appear among the species with overlap with fire tabulated in Tables 10.1 and 10.2. However, 21 of the 75 species (including *Entoloma ravinense*, see the case study in Box 10.1) are not present in the cleaned dataset due to data issues including high uncertainty about coordinates (often deliberate, due to status as threatened).

### Box 10.1. *Entoloma ravinense*

*Entoloma ravinense* (Fig. 10.3) is a distinctive, white, fan-shaped, gilled fungus up to 63 mm across with a short stem. The cap is rather woolly in young specimens and the gills become pink as spores mature. Such fan-shaped, almost stemless *Entolomas* are considered to be very rare and *E. ravinense* is no exception. In spite of intensive surveys throughout much of South Australia it has been found at only two sites on Kangaroo Island, ~30 km distant from each other at the western end of the island. As well as this narrow geographical range, *E. ravinense* has specialised environmental requirements. It is saprotrophic and seemingly specific to the bark of the sugar gum (*Eucalyptus cladocalyx*), as it has not been found associated with any other eucalypt species. Sporing bodies are found only on the undersides of thick, rotten, shed bark. Annual surveys of Kangaroo Island first found *E. ravinense* 3 years after the intense wildfires of



**Fig. 10.3.** Sporing body of *Entoloma ravinense* growing on bark of *Eucalyptus cladocalyx*. (Photo: David Catcheside)

December 2007. It is possible that thick bark shed after intense fires provides the required substrate. Although this rare fungus may require an appropriate fire regime, fire events that are too frequent and/or severe may be detrimental or even catastrophic, threatening its survival. The particularly severe and extensive wildfires of 2019–20 burnt through the only two known locations where the fungus occurs, killing or damaging the majority of trees. Abundant freshly shed sugar gum bark was seen at both locations in 2020 and 2021, but there was little evidence of fungal activity degrading the bark and no sporing bodies of *E. ravinense* were found. Based on observations after the 2007 fire, *E. ravinense* still might produce sporing bodies once 3 years have elapsed from the recent fires. However, it is possible that the spore and mycelial bank in its known range has been destroyed. In which case, this little fungus, found in 2010 and described in 2016, may be extinct. Continued monitoring of known and potential sites, including stands of *Eucalyptus cladocalyx* on the mainland, is a priority as is obtaining a pure culture for *ex situ* conservation, should the fungus re-appear.

### Constraints on interpretation

Without specific knowledge of life history, especially responses to fire and modes of dispersal and colonisation, it is difficult to determine how the 2019–20 wildfires affected the conservation status of fungi, even for species with high overlap with severe fire. Apart from the case study on *Entoloma ravinense* (Box 10.1), our analysis was not able to include detailed assessment of threats in relation to traits. Therefore, it is vital to gain further information on how fungi survive after fire. For some species occurring deep in the soil or having heat-resistant spores, fire may have minimal deleterious effects. For other species that occur only in association with aerial parts of plants or with invertebrates, fire may cause local extinction. This uncertainty points to the importance of investigating how fungi recolonise after fire, and the relative roles of mycelial persistence and spore dispersal, along with the distances over which dispersal is effective.

An important caveat of the fire overlap analysis is that distribution information is both meagre and patchy for many species of fungi, and it is likely that some species with high overlap will be found to be more widely distributed once more data are available, especially those known from few and widely separated locations. Conversely, some species with low overlap may be under-reported in areas of high fire severity. Species adapted to specific fire-sensitive microhabitats (i.e. logs, tree bark) may also be highly vulnerable to fire even though they are widely distributed.

Nevertheless, the list of species that show high fire overlap is a useful first-pass analysis to enable prioritisation of surveys, threat assessments and taxonomic studies. Further fungi identified as of potential conservation concern in relation to the 2019–2020 wildfire boundary in eastern Victoria are listed by Dell *et al.* (2020).

### Alternative strategies for determining fire impact

Two other approaches for assessing fire impacts that complement analysis of sporing body records for individual species are to (1) focus on particular ecological communities, and (2) extend metabarcoding to detect fungal community patterns (as implemented by Bowd *et al.* (2021) and Ammitzboll *et al.* (2021)) across a broader range of substrates, ecosystems and geography, including establishment of permanent monitoring plots.

In relation to particular ecological communities, those affected by fire and that contain plants that are important symbiotic partners of fungi are worth investigating. For example, some ECM fungi appear to strongly associate with *Nothofagus*, a main canopy species of Cool Temperate Rainforest (CTR). CTR patches are often larger in Tasmania while stands are often small and scattered elsewhere, but wherever it occurs CTR is often in a matrix of *Eucalyptus* forest. Fire is critical in controlling the boundary between surrounding *Eucalyptus* forest and CTR. In Tasmania, Lunn *et al.* (2018) found that fire affected rainforest species such as *Nothofagus* more strongly than eucalypts. Increased fire intensity and frequency will favour *Eucalyptus* over *Nothofagus* – this could have significant effects on any fungi restricted to *Nothofagus*. An example of the extent of loss of cover of CTR following fire comes from the O'Shannassy Catchment area to the east of Melbourne, where a 2009 fire resulted in loss of 96% of 889 ha of CTR in areas burnt at moderate to high severity (Tolsma *et al.* 2019). Further studies are needed to identify *Nothofagus*-specific fungi and their role for postfire forest regeneration.

## Conclusions

The fire overlap analysis identified some 3523 species of fungi affected by the 2019–20 fires; with several hundred species significantly affected, either by having at least half their range burnt or by having at least 20% of their range burnt by fires of high severity. However, existing distribution data are patchy for many species. In particular, species whose whole range was affected by fires of high severity were all known from very few records. Furthermore, numerous species await formal description. Therefore, to follow up, a strategic approach that combines investigation of individual prioritised species (such as arising from the present analysis) with whole of community monitoring, using metabarcoding to create baseline data against which disturbance effects can be measured, is recommended.

Land and natural resource managers rely on taxon experts to guide response and recovery, particularly after unprecedented events such as the 2019–20 wildfires. For less conspicuous taxa such as fungi, in addition to clarifying taxon delimitation, it is imperative to increase knowledge of their life history. Knowledge of functional significance, distribution, tolerance, dependency and response to episodic events is an essential ingredient for effective management and species preservation. In addition, we know that the resilience of fungal communities is important to ecosystem recovery, through their role in soil stabilisation, seedling establishment and as food resources for animals. Yet we have a limited understanding of how these relationships are affected by large wildfire events, let alone how these relationships may change in a future where fire is more common. In our changing and increasingly volatile landscape, it is essential that research and active management go hand-in-hand. We must be adaptive and responsive so that as we learn more about fungi, as well as their critical role in ecosystem function and recovery from disturbance, we can apply learnings for positive conservation outcomes.

## Recommendations

- Carry out national threat assessments of Australian fungi to allow prioritisation of species for direct management and monitoring action.
  - First step – assess at least 50 fungi species that appear to be severely affected by the 2019–20 wildfires.

- ▶ Second step – focus on fungal symbionts of other threatened taxa where loss of host will have high impact on the fungus, in particular host-specific (1) ECM fungi of fire sensitive plants, such as *Nothofagus*, (2) leaf-inhabiting fungi of threatened plants, especially fungi that undertake entire life-cycle in/on the leaf, and (3) invertebrate parasites, such as those found within the gut.
- Compile trait database as essential underpinning for assessments. Traits should include trophic mode, substrate, host preference and response to fire.
- Keep the National Species List up-to-date to facilitate access to data.
- Increase the coverage of digitisation of fungi specimens to provide better visualisation of known distributions.
- Implement baseline monitoring of fungi stratified across ecosystems, using a whole-of-community metabarcoding approach.
  - ▶ There is a need to sample not only soil, but also woody debris and living plants (especially roots) and invertebrates.
  - ▶ It is vital to link molecular operational units (mOTUs) to known taxa (and precise guild); this requires (1) bulking up reference sequence library for described species, in combination with (2) targeted collecting of 'fire sensitive' mOTUs that do not match known taxa, for formal description.
- Utilise and extend existing studies to identify species significantly affected by fire.
- Prioritise the Cool Temperate Rainforest fungal community for survey and documentation because it is particularly susceptible to fire-effects, via reduction of host range.
- Establish *ex situ* living collection (biobank), sampled across taxonomy and trophic groups, focusing on threatened species and keystone species.
- Better understand how fungi recolonise after fire, investigating the spore bank and survival as mycelium.
- Develop guidelines for ecological management and regeneration in fire-prone ecosystems, including the conservation of unburnt areas or biological legacies, such as large, old trees remaining post-fire, which act as 'refugia' and potential inoculum sources for fungal communities. Management practices should avoid soil transfer (due to pathogens) and retain organic litter as a vital substrate for many fungi and invertebrates.

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