

The compounding impacts of disease and weeds after the 2019–20 wildfires on Australian vascular plants and communities

Greg Keighery, Carl R. Gosper, Sarah Barrett, David Coates and Robert O. Makinson

Summary

- Many Australian plant species and ecological communities are threatened by weeds and diseases. The diseases affecting the most species are *Phytophthora* dieback (mostly *Phytophthora cinnamomi*) and myrtle rust (*Austropuccinia psidii*).
- For many plant species and ecological communities, weeds and disease compound the impacts of fire. Following the 2019–20 wildfires, 186 fire-affected plant species were considered to be highly vulnerable to the compounding impacts of disease, and three species to the compounding impacts of weeds.
- The interactions of fire, weeds and disease may be complex. The impacts of *Phytophthora* and myrtle rust can be magnified by fire, partly through greater vulnerability of regenerating plant tissues, and because post-fire environments provide conditions more conducive to *Phytophthora* and myrtle rust. Fires may mobilise the sporeload of myrtle rust, facilitating its broad-scale dispersal.
- At least transiently, recently burnt areas may provide suitable conditions favouring some weed species, through flushes of nutrients, reduced competition with native species and increased light, and spread of weeds may then suppress post-fire recovery of native plants. Weed impacts after fire may be especially pronounced at or near modified environments. In some cases, weeds may increase fire severity; invasive grasses may trigger changes in fire regimes and transform ecosystems. Post-fire germination of weeds may deplete their soil seed bank, providing a time-bound opportunity to then implement effective management.
- There are risks of spreading or facilitating disease and weeds associated with fire control operations (e.g. movements of vehicles from infected to uninfected

areas, and application of retardants), and such risks need to be managed through appropriate planning, operations and standards.

- Management of disease and weeds has many challenges, but adequate resourcing of pre- and post-fire monitoring and management can improve conservation outcomes.

Introduction

The decline of a significant number of Australia's vascular plants, especially threatened species, has been attributed to several key threats and threatening processes. Widespread land clearing and habitat loss, anthropogenic habitat fragmentation, climate change, invasive species including introduced diseases, inappropriate fire regimes and hydrological change are all major factors in the significant range contractions and reduction in population size of many plant species (Burgman *et al.* 2007; Silcock and Fensham 2018). Superimposed on these individual threatening processes and of potentially greater impact are the compounding effects of interactions between threats or threat syndromes (Burgman *et al.* 2007; Silcock and Fensham 2018). For example, climate change, when combined with threats such as changed fire regimes, habitat fragmentation and disease, is predicted to substantially increase the magnitude of adverse impacts on the flora (Yates *et al.* 2010). Furthermore, the exposure and/or impact of many threats is likely to differ depending on landscape age and evolutionary history (Hopper 2009; Gosper *et al.* 2021).

While the impact of major threats on the Australian flora has been broadly considered, here we focus on the interactive or compounding threats of fire, disease and weeds in the context of the 2019–20 wildfires (see Gallagher *et al.* in press). Many species, particularly those in temperate Australia, are threatened by particular combinations of fire interval, intensity and season that interrupt life cycle processes critical to survival, and/or reproduction (Keith 1996; Burgman *et al.* 2007; Shedley *et al.* 2018). Narrowly endemic serotinous obligate-seeder shrubs are especially vulnerable (see Yates *et al.* 2003): of the 418 Australian plant species recognised by Silcock and Fensham (2018) as both threatened and declining, there is a documented impact of inappropriate fire regimes for 98 taxa, with 44 considered at risk of extinction.

Particular mention has recently been made of introduced disease given the impact on numerous threatened plant species throughout Australia, especially within the conservation reserve system where some other threats may be less pervasive (Silcock and Fensham 2018; Monks *et al.* 2019). Two plant diseases are of greatest concern: *Phytophthora* dieback (in particular *P. cinnamomi*), a soil-borne water mould pathogen, and myrtle rust, which is spread by wind, water, and other vectors. Both *Phytophthora* dieback and myrtle rust have significant impacts on diverse native plant communities and many rare and threatened species, and are also characterised by major difficulties in their effective control (Barrett and Yates 2015; Makinson 2018; Makinson *et al.* 2020).

Weed invasion, regarded here as plants establishing self-propagating populations in native vegetation outside of their natural range, is a significant consequence of the extensive land clearing and habitat fragmentation that occurred across large areas of southern Australia. There are > 1000 species of weeds occurring in Australian ecosystems, among a broader group of several thousand introduced plant species naturalised in Australia, and more weeds make the transition from gardens or agriculture, or are accidentally introduced,

annually (Csurches and Edwards 1998). With such a diversity of problematic weed species, management often involves a combination of approaches directed at control of specific species (e.g. the Weeds of National Significance list) and protection of biodiversity assets from suites of weed species (Gosper *et al.* 2015).

Disturbance in the form of fire is considered a major factor exacerbating the impact of disease (Barrett *et al.* 2008; Barrett and Yates 2015; Fensham *et al.* 2020; Pegg *et al.* 2020) and weed invasion (Graham and Taylor 2018). As such, disease and weeds compound the impacts of the 2019–20 wildfires on the persistence and recovery of populations of the estimated > 9000 plant species and the structure, function and floristics of numerous ecological communities affected (see Chapters 8, 9).

Key findings

Disease–fire interactions

Plant pathogens can cause rapid and transformational changes to ecosystems and increase the risk of extinction of plant species, through increasing mortality and reducing health and reproductive output in susceptible species. In addition to direct impacts on plants, plant pathogens have cascading impacts on fauna through affecting the distribution and abundance of plant hosts, nectar, seed and other foods, and other habitat resources.

A range of plant pathogens is having significant impacts in Australian ecosystems, and the threat of new pathogen arrival or emergence is ever-present (e.g. ABARES 2021). In addition to *Phytophthora* dieback and myrtle rust, various canker fungi are impacting the Proteaceae in south-western Australia and causing stem cankers in *Eucalyptus* species, while *Armillaria* root rot (*A. luteobubulina*) causes plant death in a range of native species in south-eastern and south-western Australia (Shearer *et al.* 1997; Yates *et al.* 2021).

For both *Phytophthora* and myrtle rust, recent research has shown that impacts can be magnified by fire events, partly through greater vulnerability of plant tissues regenerating after fire. For *Phytophthora*, observations of seedling mortality after fires suggest that the post-fire environment provides conditions more conducive to the pathogen due to loss of vegetation cover and leaf litter, increased soil temperatures and changes in hydrology, while the unsuberised roots of seedlings are more vulnerable to disease (Moore 2005). In the case of myrtle rust, post-fire regrowth in resprouting plants provides optimal tissues for the pathogen (Pegg *et al.* 2020). Interactive effects of most plant pathogens and fire in Australian ecosystems are poorly known, although the combined impacts of canker and short fire intervals is an acute threat to *Banksia verticillata* (Yates *et al.* 2021), with the 2019–20 wildfires overlapping in extent with known areas of canker impact on *B. brownii* populations in the Stirling Range National Park (WA).

Spatial analyses of 2019–20 wildfire extent and known *Phytophthora* records, and modelled suitable habitat for myrtle rust, indicate that ~56% of the fire footprint intersects areas of plant pathogen occurrence (Gallagher *et al.* in press). Integrating information on plant species susceptibility to disease, plant species geographical range, fire extent and disease occurrence suggested that 186 plant species were highly vulnerable to the compounding impacts of 2019–20 wildfires and either or both *Phytophthora* and myrtle rust

(Gallagher *et al.* in press; Chapter 9). Similarly, for ecosystems, 10 ecosystem types were highly exposed to the compounding impacts of the 2019–20 wildfires and plant pathogens, having > 50% of their mapped extent burnt and with pathogen occurrence. Most of these ecosystem types were rainforests and wet eucalypt forests in eastern Australia highly exposed to fire and myrtle rust, along with the Eastern Stirling Range Montane Heath and Thicket and the Montane Mallee Thicket of the Stirling Range, highly exposed to fire and *Phytophthora* (Keith *et al.* in press; Chapter 8). These predicted impacts are being validated with field survey (see Boxes 18.1 and 18.2).

Box 18.1. *Phytophthora cinnamomi* and fire interaction: Stirling Range National Park

The threat posed by *Phytophthora* is well documented and it was listed as a Key Threatening Process under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in 2000 with a national threat abatement plan for dieback first produced in 2001 and revised in 2018 (Commonwealth of Australia 2018). The severity of *P. cinnamomi* impact is perhaps best illustrated by the work of Shearer *et al.* (2004), which estimated that 2284 (40%) described plant species and up to 50% of threatened plants in the Southwest Australian Floristic Region are susceptible. Mortality of infected individuals in the most susceptible species approaches 100% (Shearer *et al.* 2004; Barrett *et al.* 2008). Species highly susceptible to *Phytophthora* include species-rich and community dominant groups such as *Banksia* and other Proteaceae, many peas (Fabaceae) and heaths (e.g. *Leucopogon* and other Ericaceae).

The 1160 km² Stirling Range National Park (SRNP) contains more than 1500 plant taxa including some 80 endemic to the park, contributing to the SRNP being a centre of flora richness and endemism in the Southwest Australian Floristic Region global biodiversity hotspot. Disease caused by *P. cinnamomi* is considered the foremost threatening process for this flora (Barrett *et al.* 2008) with an estimated 36% of species considered to be susceptible (Shearer *et al.* 2004). The spatial extent of the disease in the SRNP has been well documented with more than two-thirds of the park considered to be infested. Other ecological processes interact with *Phytophthora* dieback to increase the risk of extinction of species and collapse of ecological communities (Barrett *et al.* 2008). The interaction between fire and *P. cinnamomi* has only recently been explored, finding increased disease impact in the SRNP after fire, particularly for fire-killed species (Moore *et al.* 2015; Barrett and Yates 2015).

A wildfire in late December 2019 burnt over 36 000 ha of the eastern SRNP. This followed a 4000 ha fire in the western SRNP (December 2019) and a 14 000 ha fire in the eastern SRNP (May 2018). Several *Phytophthora*-susceptible ecological communities were significantly impacted by these fires including the Montane Mallee Thicket of the Stirling Range and the Eastern Stirling Range Montane Heath and Thicket (see also Chapter 8). There was also a significant impact on 26 listed Threatened Flora species, many of which are highly susceptible to the pathogen and at very high risk of extinction (Barrett *et al.* 2008). Monitoring of seedling survival in susceptible species since the 2018–19 fires showed relatively low levels of mortality due to *P. cinnamomi* infection

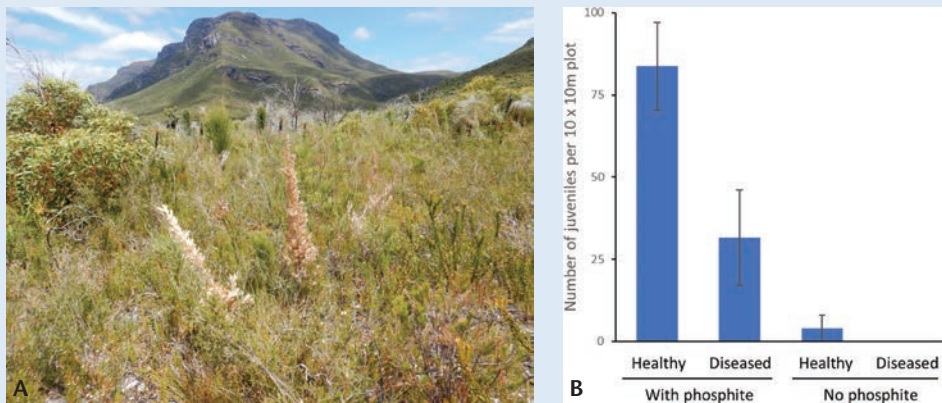


Fig. 18.1. (A) *Banksia anatona* deaths in recently burnt *Phytophthora*-infested habitat, Stirling Range National Park; (B) impact of recurrent phosphite spraying on survival of *B. anatona* recruits (mean \pm standard error) in 2022 after the 2018–19 wildfires, in plots that were originally deemed *Phytophthora*-free ('Healthy') and *Phytophthora*-infested ('Diseased') when established in 2014–16 (Barrett and Rathbone 2018). (Photo: Sarah Barrett. Graph: Carl Gosper)

during an initial period of relatively low rainfall, but very high winter–spring rainfall in 2021 has seen the onset of significant mortality of recruits in susceptible species (Fig. 18.1).

The fungicide phosphite has been used to successfully mitigate the impact of *P. cinnamomi* in the SRNP after fires in 1991 and 2000 (Barrett and Rathbone 2018), and this success appears to have continued after phosphite applications following the 2018–19 fires (Fig. 18.1). Ongoing phosphite application, disease hygiene management, and flora and ecological community monitoring are important to mitigate and understand impacts in high priority areas.

Box 18.2. Myrtle rust

The myrtle rust pathogen (*Austropuccinia psidii*), an introduced fungus, affects plants of the Myrtaceae family. A single biotype was detected in Australia in 2010, and is now naturalised along almost the entire eastern seaboard east of the Great Dividing Range and in parts of the Northern Territory. The Australian host range exceeds 350 species, ~15% of which are known or thought likely to be at serious risk. Several hosts in catastrophic decline are listed as Critically Endangered under Queensland, New South Wales or Commonwealth legislation, with others likely to follow (Makinson 2018; Makinson *et al.* 2020). Other biotypes of *A. psidii* represent an additional biosecurity threat; one strain with a particular affinity for eucalypts has caused major economic losses in South American plantations.

Myrtle rust occurs mainly in mesic vegetation types but can extend into drier sclerophyll associations in suitable microhabitats and seasons. The pathogen is biotrophic, attacking new growth (seedlings, seasonal flush, and post-fire resprouts;

Fig. 18.2), and in highly susceptible species can cause death within a few reinfection cycles. The life cycle is rapid (as little as 10 days), enabling rapid increase when conditions permit. The spores are highly mobile on wind, animals and via human vectors.

Fire will destroy infected plants and a proportion of rust spores, but dry conditions and fire updraught will also mobilise sporeload high into the air column, facilitating dispersal over tens or hundreds of kilometres. Recolonisation may easily occur once weather conditions are right, from unburnt patches within a fire footprint or adjacent areas. Regenerative growth, usually on multiple hosts, provides an ideal trophic base. The dominance of Myrtaceae in forest, heath and woodland systems tends to ensure that suitable tissue is available for most of the year, increasing the rust's capacity to re-establish after fire.

Studies of post-fire interactions of myrtle rust disease and its hosts have been limited to subtropical east-coast heathlands and *Melaleuca quinquenervia* floodplain woodlands. Floristic changes and increased weed invasion are known as non-fire-related effects of repeated severe infection in a wet sclerophyll/rainforest transition system (Pegg *et al.* 2017), and can be expected to be amplified after fire on fertile substrates. Fensham and Radford-Smith (2021) noted the potential for pre-fire interactions between myrtle rust and drought in such systems to affect post-fire outcomes.

In a study of *Melaleuca* woodlands, which often fringe or overstand freshwater wetlands, Pegg *et al.* (2018) found regeneration failure accentuated by post-fire



Fig. 18.2. (A) Post-fire sucker resprouts of scrub turpentine (*Rhodamnia rubescens*) trees showing severe infection by myrtle rust (*Austropuccinia psidii*), north-east NSW, 2020–21; (B) myrtle rust infection on reshooting fire-affected needlebark stringybark (bastard tallowwood) (*Eucalyptus planchoniana*), north-east NSW, 2020–21. (Photos: Geoff Pegg)

additive effects of myrtle rust and invertebrate herbivores, particularly mirid bugs (*Eucerochoris suspectus*). Highly variable levels of *M. quinquenervia* seedling resistance to myrtle rust within and between populations are known (Pegg *et al.* 2018), and the interactions of fire, pathogen, insects and local genetics need to be further evaluated.

In a study of coastal heathland after the 2019–20 fires, Pegg *et al.* (2020) found some level of infection by myrtle rust on nearly all regenerating Myrtaceae species present, and on 69% of all myrtaceous regenerants within 3 months, noting that ‘the speed at which we observed re-introduction of *A. psidii* on regenerating Myrtaceae from surrounding reservoirs was remarkable’.

Weed–fire interactions

Weeds are a major threat to plant diversity and ecosystem function, having impacts as diverse as competition for resources (e.g. light, water, nutrients) and pollinator and seed disperser fauna, facilitation of feral honeybee dominance, inducing changes in nutrient cycling and the availability of habitat for fauna.

Weeds can have a direct influence on fire regimes and events, through changing the flammability of vegetation via differences in the spatial and temporal distribution of fuel and fuel dryness. Weedy grasses, in particular, can foster reduced fire intervals and greater fire occurrence when established in forests, woodlands and shrublands with naturally shrubby understoreys – a globally significant phenomenon known as the grass–fire cycle (D’Antonio and Vitousek 1992). For many weeds, fires enhance spread and abundance through providing a seed germination stimulus, temporarily eliminating competition with established native vegetation, and initiating a flush of nutrients from ash.

The relationship between fire and weed invasion is complex and highly dependent on context; hence the likelihood that the 2019–20 wildfires facilitated or enhanced problematic weed invasions will be spatially variable. Weed invasions into native vegetation are strongly associated with proximity to, and dispersal pathways for, weed propagules (seed and vegetative material) and disturbance, so tend to be greater on native vegetation edges and closer to towns, agricultural land, roads and mining activity (Gosper *et al.* 2011, 2015). Land uses that lead to elevated soil nutrient levels, such as agriculture and settlements, strongly facilitate invasions (Fisher *et al.* 2006, 2009). Indeed, many Australian ecosystems with highly infertile soils are resistant to weed invasion, even after fire, as long as soil nutrient levels are not elevated (Gosper *et al.* 2011). The commonly used fire retardant, Phos-Chek, can contribute to elevated soil nutrient levels, with consequent implications for weed invasion (Bell *et al.* 2005). Thus, locations where the 2019–20 fires are likely to have had the greatest impact on facilitating weed invasions are along the interface between native vegetation and agriculture, urban areas and roads.

National desktop assessments following the 2019–20 wildfires suggested that the impacts of weeds post-fire across the full ranges of plant species and ecological communities was less than other important threats (with three fire-affected plant species considered highly vulnerable to compounding impacts of weeds), perhaps partly a function of poor representation of weed distributions in spatial datasets (Gallagher *et al.* in press; Keith *et al.* in press).

Nevertheless, significant impacts of weeds on native flora and ecological communities are emerging post-fire, including on orchids (Chapter 9), warm temperate rainforests of Victoria (Chapter 8) and threatened Swan Coastal Plain ecological communities (see Box 18.3).

Although fire can facilitate weed invasion, it also offers an opportunity for weed control. As fires provide a major germination stimulus, they deplete weed soil seed banks, which, if coupled with effective post-fire weed management before new seed input, can contribute to the restoration of ecosystem composition and function (Brown and Brooks 2002). The timing of post-fire weed management to achieve effective weed control varies between weed species based on their maturation time, but for weedy grasses and herbs the first growing season post-fire is crucial.

Box 18.3. Weed invasion post-fire in threatened ecological communities of the Swan Coastal Plain

In December 2019, a wildfire in the Yanchep area north of Perth impacted stands of the EPBC Act-listed tuart (*Eucalyptus gomphocephala*) woodlands and forests of the Swan Coastal Plain threatened ecological community. Tuart is endemic to the Swan Coastal Plain. Studies of the impacts of previous major high-severity bushfires in tuart woodlands provide a basis for understanding post-fire weed issues arising from the 2019 Yanchep fire.

Landscape-scale wildfires have impacted the Yalgorup National Park area south of Perth in 1996, 2006 and 2016, with the 2016 fire being very intense. Quadrat-based resampling was conducted in 2017, in the second spring after the 2016 fire, of plots established in 2007 (Keighery *et al.* 2009). The 2017 sampling recorded significant seedling growth and resprouting of larger tuarts. However, it was noticeable that many of the older tuarts (over 37%) that contained hollows had died in the fire. Weedy species were more noticeable, numerous and more species diverse post-fire. Prior to the fire, the mean richness (per quadrat) of weed species was 7.7. After fires mean weed richness increased to 11, including annual grasses (*Bromus diandrus*, *Lolium rigidum*), weeds germinating from kangaroo faeces (*Lotus suaveolens*, *Medicago* spp., *Stellaria media*) and wind-dispersed weeds (*Arctotheca calendula*, *Urospermum picroides*). Mass flowering and seeding of several previously inconspicuous bulbous weeds occurred (*Freesia* hybrids and *Morea flaccida*).

In the clay pans of the Swan Coastal Plain threatened ecological community, the 2016 wildfire in Yalgorup National Park initiated population collapse of a community dominant, *Leptomeria ellytes*, and led to significant increases in weeds. Pre-fire sampling showed that this community normally has a species richness of 40 native plant species, with another 15 weed species, per 100 m² plot – consistent with high weed richness in other occurrences of this community (Gibson *et al.* 2005). After the fire, weeds increased by 10 annual species per plot on average, largely dispersed via kangaroo faeces derived from foraging in adjacent farmland. These weed species remained in the area when the community was surveyed in 2020. Weed invasion, particularly after disturbances such as fire, is regarded as one of the key processes threatening both tuart and clay pan communities (DPaW 2015; DEE 2019).

Recommendations

For *Phytophthora* and myrtle rust, there is low feasibility of eradication or prevention of all impacts on native flora once the pathogen has become established, based on currently available pathogen management options. This reality, combined with compounding impacts with fire, indicates that pathogen management in fire-prone ecosystems will be most effective through considering the following points:

- While recognising that disease and weed hygiene procedures are well embedded in many organisations involved in fire operations in natural ecosystems, the risk of inadvertent dispersal of pathogens, such as through *Phytophthora*-infested soil attached to machinery, equipment and clothing, can be minimised by continued and enduring attention to hygiene management through all stages of fire planning and operations. The same types of precautions apply to vehicles, equipment and personnel moving from established myrtle rust zones to uninfected States or areas.
- Expansion of species and population representation of pathogen-susceptible species in *ex situ* germplasm collections, and where appropriate translocations to pathogen-free locations and/or the selection and reintroduction of pathogen-resistant genotypes, will assist in buffering the risk of population extinctions in the wild.
- Adequate resourcing of pre- and post-fire pathogen management and monitoring can improve conservation outcomes, as pathogen impacts can be greater after fire but can be mitigated in some situations with appropriate controls.
- Adequate resourcing of research into novel pathogen management techniques, methods of pathogen detection and quantification of impacts on biodiversity may improve pathogen management. While significant advances in knowledge have been made over recent decades, pathogen management is currently limited by a lack of effective tools for mitigation of impacts and knowledge of the extent of impact in natural ecosystems with variation in environmental conditions.

The availability and effectiveness of tools for post-fire weed control varies. Considering the following points may lead to improved weed management after significant fire events:

- Innovative approaches are needed for resourcing post-fire weed control and developing collaborations with community groups and other partners that can assist in on-ground actions. Tools for the control of some weeds after fire in natural ecosystems are well established and effective, for example the selective control of grassy weeds by the ‘fops’ group of herbicides (Brown and Brooks 2002). In these cases, effective post-fire weed management is largely a question of adequate and timely deployment of resources. However, this is by no means a simple task, as human, equipment and financial resources of many land management agencies will be stretched in the aftermath of fire emergencies, due to the significant role many of these agencies play in fire emergency response and other fire-related conservation actions (see Chapter 23).
- Ongoing research is needed into chemical, ecosystem management and biological weed control approaches, and their integration, for weed-ecosystem combinations. Such enhanced knowledge may be most needed where effective weed control methods after fire are currently lacking, such as for weedy bulbs in ephemeral wetlands.
- Taking into account locations where fire retardant use intersects with important biodiversity values could assist in targeting weed control efforts. Furthermore, additional

research is warranted on the weed invasion implications of fire retardants, given preliminary research suggesting retardants can alter soil properties. Needless to say, use of fire retardants will remain crucial in fire emergencies for protection of life and property.

References

- ABARES (2021) 'The National Priority List of Exotic Environmental Pests, Weeds and Diseases: Information Paper (Version 2.0)'. Department of Agriculture, Water and the Environment, Canberra.
- Barrett S, Rathbone D (2018) Long-term phosphite application maintains species assemblages, richness and structure of plant communities invaded by *Phytophthora cinnamomi*. *Austral Ecology* **43**, 360–374. doi:10.1111/aec.12574
- Barrett S, Yates CJ (2015) Risks to a mountain summit ecosystem with endemic biota in southwestern Australia. *Austral Ecology* **40**, 423–432. doi:10.1111/aec.12199
- Barrett S, Shearer BL, Crane CE, Cochrane A (2008) An extinction-risk assessment tool for flora threatened by *Phytophthora cinnamomi*. *Australian Journal of Botany* **56**, 477–486. doi:10.1071/BT07213
- Bell T, Tolhurst K, Wouters M (2005) Effects of fire retardant Phos-Chek on vegetation in eastern Australian heathlands. *International Journal of Wildland Fire* **14**, 199–211. doi:10.1071/WF04024
- Brown K, Brooks K (2002) *Bushland Weeds: A Practical Guide to their Management*. Environmental Weeds Action Network, Greenwood.
- Burgman MA, Keith D, Hopper SD, Widyatmoko D, Drill C (2007) Threat syndromes and conservation of the Australian flora. *Biological Conservation* **134**, 73–82. doi:10.1016/j.biocon.2006.08.005
- Commonwealth of Australia (2018) *Threat Abatement Plan for Disease in Natural Ecosystems caused by Phytophthora cinnamomi*. Commonwealth of Australia, Canberra.
- Csurches S, Edwards R (1998) *Potential Environmental Weeds in Australia*. Environment Australia, Canberra.
- D'Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* **23**, 63–87. doi:10.1146/annurev.es.23.110192.000431
- Department of Parks and Wildlife (DPaW) (2015) *Interim Recovery Plan 2015–2020 for Clay Pans of the Swan Coastal Plain (Swan Coastal Plain Community Types 7, 8, 9 and 10a) and Clay Pans with Mid Dense Shrublands of Melaleuca lateritia Over Herbs*. Interim Recovery Plan No. 354. DPaW, Perth.
- Department of the Environment and Energy (DEE) (2019) Approved conservation advice (incorporating listing advice) for the Tuart (*Eucalyptus gomphocephala*) woodlands and forests of the Swan Coastal Plain ecological community. Department of the Environment and Energy, Canberra, <<http://www.environment.gov.au/biodiversity/threatened/communities/pubs/153-conservation-advice.pdf>>.
- Fensham RJ, Radford-Smith J (2021) Unprecedented extinction of tree species by fungal disease. *Biological Conservation* **261**, 109276. doi:10.1016/j.biocon.2021.109276
- Fensham R, Carnegie AJ, Laffineur B, Makinson RO, Pegg GS, *et al.* (2020) Imminent extinction of Australian Myrtaceae by fungal disease. *Trends in Ecology & Evolution* **35**, 554–557. doi:10.1016/j.tree.2020.03.012
- Fisher JL, Veneklaas EJ, Lambers H, Loneragan WA (2006) Enhanced soil and leaf nutrient status of a Western Australian Banksia woodland community invaded by *Ehrharta calycina* and *Pelargonium capitatum*. *Plant and Soil* **284**, 253–264. doi:10.1007/s11104-006-0042-z

- Fisher JL, Loneragan WA, Dixon K, Delaney J, Veneklaas EJ (2009) Altered vegetation structure and composition linked to fire frequency and plant invasion in a biodiverse woodland. *Biological Conservation* **142**, 2270–2281. doi:10.1016/j.biocon.2009.05.001
- Gallagher RV, Allen SP, Mackenzie BDE, Keith DA, Nolan RH, *et al.* (in press) An integrated approach to assessing abiotic and biotic threats to post-fire plant species recovery: lessons from the 2019–20 Australian megafires. *Global Ecology and Biogeography*. doi:10.1111/geb.13478
- Gibson N, Keighery GJ, Lyons MN, Keighery BJ (2005) Threatened plant communities of Western Australia. 2 The seasonal clay-based wetland communities of the South West. *Pacific Conservation Biology* **11**, 287–301. doi:10.1071/PC050287
- Gosper CR, Yates CJ, Prober SM, Williams MR (2011) Fire does not facilitate invasion by alien annual grasses in an infertile Australian agricultural landscape. *Biological Invasions* **13**, 533–544. doi:10.1007/s10530-010-9847-z
- Gosper CR, Prober SM, Yates CJ, Scott JK (2015) Combining asset- and species-led alien plant management priorities in the world's most intact Mediterranean-climate landscape. *Biodiversity and Conservation* **24**, 2789–2807. doi:10.1007/s10531-015-0973-x
- Gosper CR, Coates DJ, Hopper SD, Byrne M, Yates CJ (2021) The role of evolutionary history in the distribution, biogeography and conservation of Threatened flora in the Southwest Australian Floristic Region. *Biological Journal of the Linnean Society* **133**, 394–410. doi:10.1093/biolinnean/blaa141
- Graham M, Taylor K (2018) 'Fire, weeds and the native vegetation of New South Wales'. Report by Hotspots Fire Project, Nature Conservation Council of New South Wales and New South Wales Rural Fire Service, Sydney.
- Hopper SD (2009) OCBIL theory: towards an integrated understanding of the evolution, ecology and conservation of biodiversity on old, climatically buffered, infertile landscapes. *Plant and Soil* **322**, 49–86. doi:10.1007/s11104-009-0068-0
- Keighery GJ, Keighery BJ, Longman VE (2009) *A Preliminary List of the Flora and Significant Flora of Yalgorup National Park*. Department of Environment and Conservation, Perth.
- Keith D (1996) Fire-driven extinction of plant populations: a synthesis of theory and review of evidence from Australian vegetation. *Proceedings of the Linnean Society of New South Wales* **116**, 37–78.
- Keith DK, Allen SP, Gallagher RV, Mackenzie BDE, Auld TD, *et al.* (in press) Fire-related threats and transformational change in Australian ecosystems. *Global Ecology and Biogeography*. doi:10.1111/geb.13500
- Makinson RO (2018) *Myrtle Rust Reviewed: The Impacts of the Invasive Pathogen Austropuccinia psidii on the Australian Environment*. Plant Biosecurity Cooperative Research Centre, Canberra, <<http://www.apbsf.org.au/wp-content/uploads/2018/11/Myrtle-Rust-reviewed-June-22-2018-web.pdf>>.
- Makinson RO, Pegg GS, Carnegie AJ (2020) Myrtle rust in Australia – a national action plan. Australian Plant Biosecurity Science Foundation, Canberra, Australia, <<http://www.apbsf.org.au/myrtle-rust/>>.
- Monks L, Barrett S, Beecham B, Byrne M, Chant A, *et al.* (2019) Recovery of threatened plant species and their habitats in the biodiversity hotspot of the Southwest Australian Floristic Region. *Plant Diversity* **41**, 59–74. doi:10.1016/j.pld.2018.09.006
- Moore NA (2005) Role of fire on *Phytophthora cinnamomi* in the Stirling Range National Park, Western Australia. BSc (Hons) thesis. Murdoch University, Murdoch.
- Moore N, Barrett S, Howard K, Craig MD, Bowen B, *et al.* (2015) Time since fire and average fire interval are the best predictors of *Phytophthora cinnamomi* activity in heathlands of south-western Australia. *Australian Journal of Botany* **62**, 587–593. doi:10.1071/BT14188
- Pegg G, Taylor T, Entwistle P, Guymer G, Giblin F, *et al.* (2017) Impact of *Austropuccinia psidii* (myrtle rust) on Myrtaceae-rich wet sclerophyll forests in south east Queensland. *PLoS One* **12**, e0188058. doi:10.1371/journal.pone.0188058

- Pegg GS, Lee DJ, Carnegie AC (2018) Predicting impact of *Austropuccinia psidii* on populations of broad leaved Melaleuca species in Australia. *Australasian Plant Pathology* **47**, 421–430. doi:10.1007/s13313-018-0574-8
- Pegg GS, Entwistle P, Giblin FR, Carnegie AJ (2020) Fire and rust – the impact of *Austropuccinia psidii* (myrtle rust) on regeneration of Myrtaceae in coastal heath following wildfire. *Southern Forests* **82**, 280–291. doi:10.2989/20702620.2020.1819154
- Shearer BL, Byrne A, Dillon M, Buehrig R (1997) Distribution of *Armillaria luteobubalina* and its impact on community diversity and structure in *Eucalyptus wandoo* woodland of southern Western Australia. *Australian Journal of Botany* **45**, 151–165. doi:10.1071/BT95083
- Shearer BL, Crane CE, Cochrane A (2004) Quantification of the susceptibility of the native flora of the South-West Botanical Province, Western Australia, to *Phytophthora cinnamomi*. *Australian Journal of Botany* **52**, 435–443. doi:10.1071/BT03131
- Shedley E, Burrows N, Yates CJ, Coates DJ (2018) Using bioregional variation in fire history and fire response attributes as a basis for managing threatened flora in a fire-prone Mediterranean climate biodiversity hotspot. *Australian Journal of Botany* **66**, 134–143. doi:10.1071/BT17176
- Silcock JL, Fensham RJ (2018) Using evidence of decline and extinction risk to identify priority regions, habitats and threats for plant conservation in Australia. *Australian Journal of Botany* **66**, 541–555. doi:10.1071/BT18056
- Yates CJ, Abbott I, Hopper SD, Coates DJ (2003) Fire as a determinant of rarity in the south-west Western Australian global biodiversity hotspot. In *Fire in Ecosystems of South-west Western Australia: Impacts and Management*. (Eds I Abbott and N Burrows) pp. 395–420. Backhuys Publishers, Leiden.
- Yates CJ, McNeill A, Elith J, Midgley GF (2010) Assessing the impacts of climate change and land transformation on *Banksia* in the South West Australian Floristic Region. *Diversity and Distributions* **16**, 187–201. doi:10.1111/j.1472-4642.2009.00623.x
- Yates CJ, Barrett S, Dilly M, Hopper SD, Stewart B, *et al.* (2021) Modelling the impact of canker disease and fire regimes on the population dynamics and extinction risk of the Critically Endangered and granite endemic shrub *Banksia verticillata* R.Br. *Australian Journal of Botany* **69**, 274–284. doi:10.1071/BT20156