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Blackened roots and green shoots: emerging trends in decline and recovery in Australian plant species after the 2019–20 wildfires

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Summary

- Australian plant diversity is maintained by variable fire regimes, and a single fire event – even one as large as the 2019–20 season – will have both positive and negative outcomes for species.
- We describe how impacts were assessed after the 2019–20 fires using vulnerability assessments and evidence from field-based observations.
- Many species are recovering well, and surprise findings of new populations are being reported across burnt areas.
- However, the 2019–20 fires have compounded threats already active across the range of many species, including Wollemi pine (*Wollemia nobilis*), Stirling Range dryandra (*Banksia montana*) and some terrestrial orchids.

Introduction

Previous analyses found that the 2019–20 wildfires of eastern and southern Australia burnt across suitable habitat for 17 197 plant taxa (hereafter ‘species’) – 69% of the currently described flora of Australia (Gallagher *et al*. 2021; Table 9.1). Collections made since 1950 confirmed the relatively recent presence of 9092 of these species across the fire grounds, including 587 plants listed as threatened under national legislation (44% of Australia’s threatened plants). For many plant species, the 2019–20 fires brought welcome renewal to populations by promoting recruitment. However, the presence of several key pre-existing threats may jeopardise the long-term viability of many fire-affected populations and some species. Identifying which species may be most vulnerable to poor recovery involves (1) undertaking a rapid vulnerability

Table 9.1. Extent of area burnt in the 2019–20 fires across the ranges of 26 062 plant species.

All analyses were limited to fires within bioregions in the southern half of the continent. Plant geographical ranges were sourced from both cleaned occurrence records from the Australian Virtual Herbarium (https://avh.chah.org.au/) and species distribution modelling (see Andrew *et al.* 2021) or range mapping conducted for listing advice under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) for threatened taxa. The spread of values provided reflects the use of these different range size estimates.

Species group	Count	Plant species with range data available	Plant species impacted by 2019–20 fires (%)	Plant species impacted by 2019–20 fires (count)	Plant species with range > 90% burnt (count (%))	Plant species with range > 50% burnt (count (%))	Plant species with range > 30% burnt (count (%))
NSW endemics	1320	1248	77–92%	956–1152	52–104 (4–8%)	306–311 (25%)	519–626 (42–50%)
WA endemics	8952	8578	32–68%	2754–5822	4–10 (< 1%)	40–45 (< 1%)	98–190 (1–2%)
Vic endemics	408	362	32–80%	113–278	12–13 (3–4%)	28–31 (8–9%)	43–57 (12–16%)
SA endemics	488	457	31–70%	160–319	3–6 (0–1%)	37–38 (8%)	56–58 (12–13%)
Qld endemics	3629	3436	11–54%	388–1865	1–3 (< 1%)	3–11 (< 1%)	19–30 (< 1%)
Tas endemics	543	525	9–77%	49–402	0 (0%)	0 (0%)	1–2 (< 1%)
ACT endemics	6	6	33–83%	2–5	0 (0%)	1 (17%)	1 (17%)
EPBC Act listed species	1335	1333	44%	585	35 (3%)	90 (7%)	148 (11%)
Listed as threatened in NSW	700	656	59–91%	386–598	32–34 (5%)	79–107 (12–16%)	139–199 (21–30%)
Listed as threatened in WA	436	434	13–51%	56–220	1–2 (< 1%)	4–12 (1–3%)	24–25 (6%)
Listed as threatened in Vic	1770	1617	60–93%	963–1499	17–18 (1%)	76–95 (5–6%)	229–249 (14–15%)
Listed as threatened in SA	807	769	53–87%	404–665	3–4 (< 1%)	19–21 (2–3%)	34–40 (4–5%)
Listed as threatened in Qld	935	899	15–43%	138–387	0–2 (< 1%)	3–14 (< 1%)	31–38 (3–4%)
Listed as threatened in Tas	460	434	59–79%	257–344	0–1 (< 1%)	2 (< 1%)	14–24 (3–6%)
Listed as threatened in ACT	13	13	31–85%	4–11	0–1 (0–8%)	0–1 (0–8%)	1–2 (8–15%)
All other taxa	7976	7969	40–65%	3203–5197	2–6 (< 1%)	23–71 (< 1%)	216–342 (3–4%)
Total	**26 062**	**25 052**	**36–69%**	**9092–17197**	**90–153 (< 1%)**	**517–593 (3%)**	**1319–1461 (5–6%)**

assessment, and (2) conducting field surveys to confirm, or revise, predictions about at-risk taxa.

To assess vulnerability to poor post-fire recovery, a framework that uses information on the extent of burning across a species' range, species fire-response traits and susceptibility to 11 key threats (Table 9.2; Auld *et al.* unpublished) was developed. From March to July 2020, this framework was tested using geographical range data (Andrew *et al.* 2021), trait information (Falster *et al.* 2021) and knowledge of the susceptibility of plant species to threats (Gallagher 2020). The primary goal of that desktop exercise was to identify the species in urgent need of surveys and conservation management interventions. In many instances ongoing monitoring remains essential to determine population recovery. This was the first prioritisation exercise across the entire breadth of the Australian flora, and it formed the evidence base for post-fire conservation prioritisation for plants by the Commonwealth and some state governments.

Of the 26 062 plant species assessed in the vulnerability analysis (Gallagher *et al.* 2021), 486 were prioritised as requiring immediate actions. These taxa had more than 80% of their range burnt or were listed as Endangered or Critically Endangered, or were considered as highly vulnerable to two or more threats. Threats potentially affecting the most species included pre-fire drought, high-severity fire, disease, and the cumulative impact of short fire intervals (Table 9.2). Overall, at least 831 species were ranked at high vulnerability to the interactive effects of existing threats and the impacts of the 2019–20 fires (Table 9.2).

While a desktop assessment could be completed rapidly to help inform decision making, the findings required confirmation. For instance, the outcomes of spatial analysis of vulnerability rely on the precision of datasets describing fire, as well as the quality of occurrence data and threat mapping. For many species, information on fire response remains unknown and therefore sensitivity to fire can only be assessed through field visits.

Table 9.2. Eleven criteria used to assess the vulnerability of plant species to recovery post-fire and their ranking after assessment.

Values in body of table are numbers of plant taxa. Criteria are described fully in Auld *et al.* (unpublished) and all methods for assessment are provided in Auld *et al.* (2020) and Gallagher (2020).

Criteria	High	Medium	Low	None	Data deficient
A. Interactive effects of fire and drought	235	340	10 375	14 102	1010
B. Short fire intervals (impacts of high fire frequency)	147	485	14 718	9498	1214
C. Post-fire herbivore impacts	97	47	4820	14 425	6673
D. Fire–disease interactions	186	444	3117	17 537	4778
E. High fire severity	258	474	16 080	8240	1010
F. Weed invasion	3	8	11 859	13 182	1010
G. Elevated winter temperatures or changed temperature regimes	9	19	235	25 654	145
H. Fire sensitivity	13	23	332	25 693	1
I. Post-fire erosion	4	17	5766	19 265	1010
J. Cumulative exposure to high fire frequency	291	593	1806	8543	14 829
K. Other plausible threats or expert-driven nominations	35	0	0	0	26 027

Below we use a set of examples to illustrate impacts and recovery of species and plant communities following the 2019–20 fires. We conclude with recommendations that aim to enhance plant conservation in a future likely to be marked by an increasing incidence of such wildfires.

Assessing impacts on iconic threatened species

Wollemi pine

Wollemi pine (*Wollemia nobilis*) is a Critically Endangered palaeoendemic conifer, restricted to a single population comprising just 46 mature individuals in Wollemi National Park, NSW (Mackenzie and Auld in press). It is a long-lived rainforest tree that reproduces sexually via seed and vegetatively via basal coppicing, both in the absence of, and in response to, disturbance (Mackenzie *et al*. 2021). Individual trees are usually multi-stemmed, each of which can live more than 400 years. There is no seed bank, but the population contains a bank of shade-tolerant, slow-growing juveniles (Zimmer *et al*. 2014).

The wild population of Wollemi pine came under threat during the 2019–20 fires and was the subject of an intensive, multifaceted, and much-lauded, multi-agency fire suppression effort (Hannam 2020; Fig. 9.1). The groves were still variously impacted by understorey fires; however, the intervention probably reduced the severity of impacts (Mackenzie and Auld).

Wollemi pine was assessed as high risk of poor recovery in post-fire vulnerability assessments (Auld *et al*. 2020; Gallagher 2020). The species' entire range was burnt and key risk drivers in these assessments included the prevalence of high fire frequency (Criterion B, Table 9.2), pathogens (Criterion D), and fire sensitivity (Criterion H) due to the species' longevity, slow growth and maturation, and vulnerability to basal collapse following prolonged charring (Auld *et al*. unpublished).

Post-fire inspections revealed that the majority of adult trees had survived the fires with their upper canopies intact; however, several large adults lost significant trunks via basal charring and impacts from falling rocks and trees (Mackenzie, Clarke and Auld, unpublished data). Delayed mortality of several individuals known to be infected with the pathogen *Phytophthora cinnamomi* was also noted post-fire and may be attributable to the interactive effects of disease and fire. Juvenile trees were disproportionately impacted by the fires with 95% of individuals < 2 m tall eliminated and ~60% of individuals > 2 m tall topkilled, only half of which had resprouted at 1.5 years post-fire (Mackenzie, Clarke and Auld, unpublished data). It is likely to take a decade or more to re-establish the juvenile cohort of plants. Three translocated populations established between 2012 and 2019 were also heavily impacted by the fires, although two of the populations have subsequently been re-established through additional planting (Mackenzie *et al*. 2021).

This case highlights the vulnerability of resprouters – especially long-lived species that are slow to develop fire-resistance and/or have low population turnover – to frequent or severe fire (although even fires of low severity may still cause significant damage, as was observed following the 2019–20 fires). A living collection and a seed bank of Wollemi pine maintained at the Australian Botanic Garden contains a broad range of genetic material from the wild population, which may enable the potential reintroduction of genetic diversity, if required (see also Chapter 27). Active fire management will be integral to the ongoing survival and conservation of the remaining wild populations to ensure appropriate fire-free intervals for post-fire recovery and recruitment (Mackenzie and Auld in press).

Fig. 9.1. Impacts of the 2019–20 fires on Wollemi pine and early stages of post-fire recovery. (Photos: (A) John Spencer/NPWS, (B) Phil Lamrock/NPWS, (C) Steve Clarke/DPE, (D, E) Berin Mackenzie/DPE)

Orchids

Orchids are considered iconic by many Australians and are subject to much public interest. Their response to fire is determined by the traits of their life cycle, as well as fire severity and timing. Metcalfe's greenhood (*Pterostylis metcalfei*) (Fig. 9.2), listed as Endangered in New South Wales, is a terrestrial orchid restricted to three populations, with many hundreds of plants in dozens of clusters, in north-eastern New South Wales (Metcalfe 2017). Most of these plants were burnt in a particularly intense wildfire in November 2019. Post-fire surveys (Eco Logical Australia 2021) documented a significant decline in the number of plants. Burnt areas originally known to contain hundreds of plants yielded only nine and 24 plants in 2020 and 2021 respectively. Most clusters of plants appear to have disappeared with no leaves or flowers visible in the two post-fire surveys. In contrast, a small adjacent, unburnt patch sampled in the same surveys yielded 97 and 89 plants respectively.

Fig. 9.2. (A) Metcalfe's greenhood; and (B) dense, post-fire infestation of invasive plants such as flax-leaf fleabane and spear thistle are compromising the recovery of Metcalfe's greenhood. (Photos: Lachlan Copeland)

The apparent decline in Metcalfe's greenhood in the severely burnt areas is probably a result of both direct mortality and habitat changes driven by the colonisation of weeds after fire (Criteria E and F respectively, Table 9.2). Death during or immediately after the fires was probably caused by burning that went deep into the leaf litter and killed the shallow tubers from which plants reshoot each year. Vegetation regrowth following the fires has also resulted in a very different physiognomic structure. Prior to the 2019 fire, the orchids grew in a tall moist open forest with a sparse shrub layer, a moderate density of *Poa sieberiana*, and relatively few weeds. The same area now has a very dense layer of introduced forbs such as flax-leaf fleabane (*Erigeron bonariensis*) and spear thistle (*Cirsium vulgare*). The decline of Metcalfe's greenhood in the burnt areas highlights how high fire severity and weed invasion can interact to create negative impacts on some ground orchids.

Stirling Range dryandra

The Critically Endangered Stirling Range dryandra (*Banksia montana*) is a fire-killed shrub with a canopy-held seed bank that is endemic to higher-elevation portions of the eastern Stirling Range in south-western Australia (Fig. 9.3). In common with many other threatened flora of the Eastern Stirling Range Montane Heath and Thicket ecological community (see Chapter 8), the Stirling Range dryandra is threatened by the combination of high susceptibility to *Phytophthora* dieback and exposure to short fire intervals (Criteria D and B respectively, Table 9.2) with a 9-year interval between fires in 1991 and 2000 being particularly damaging (Barrett and Yates 2015). Although known from six populations historically, two of these became extirpated by 2000 (Barrett *et al*. 2005).

In 2017, a full census of all populations recorded a total of 38 reproductively mature individuals, ranging in age from 17 years (recruited after the 2000 fire) to > 45 years, along with a handful of juveniles (Fig. 9.3). A fire in May 2018 killed all but eight of the mature individuals but led to the post-fire recruitment of 1354 seedlings – a much larger seedling cohort than seen after the 9-year interval in 2000. Another fire in December 2019 killed the remaining mature individuals, along with 36 of the seedlings that had germinated in 2018. The species was subsequently assessed as high risk in post-fire vulnerability assessments, and needing urgent intervention (Gallagher 2020).

Post-fire recruitment after the 2019 fire was more modest than in 2018, perhaps related to senescence in the > 45-year-old plants, and did not offset the mortality in the 2018

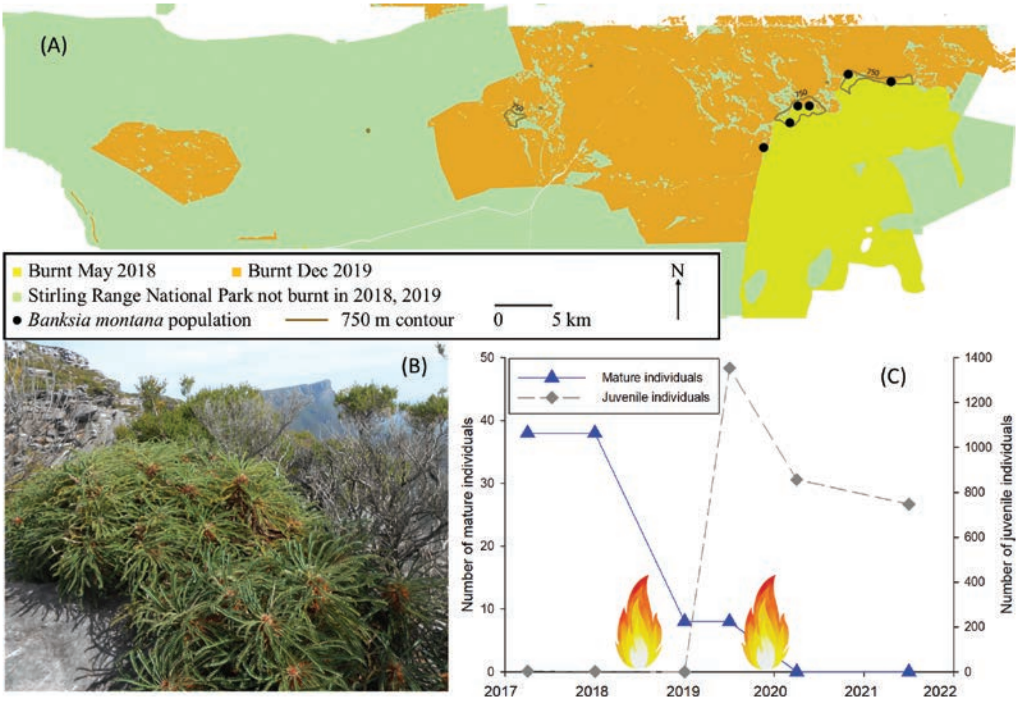

Fig. 9.3. Impacts of recent fires on Stirling Range dryandra: (A) Stirling Range National Park, showing the extent of fires in May 2018 and December 2019 and known occurrences of Stirling Range dryandra (note that the two most southerly populations became extinct by 2000); (B) mature plants pre-fire; and (C) temporal trends in the total number of reproductively mature and juvenile individuals over time, aggregated across all populations, in relation to the two recent fire events. Note that mature and juvenile individual axes have different scales. (Photo: (B): Sarah Barrett; Images: (A, C): Carl Gosper)

cohort. While the size of the juvenile cohort is still large, and has the potential to lead to a larger mature plant cohort than existed before the fires in 2018 and 2019, substantial decline in the number of seedlings over time is expected associated with *Phytophthora* dieback and mortality due to browsing, drought and competition.

Currently, there are no reproductively mature individuals in the wild, although small numbers occur in two conservation translocations outside the species' natural range. The combination of being a fire-killed species with a canopy-held seed bank, having a long juvenile period associated with a low-productivity ecosystem (Barrett and Yates 2015; Gosper *et al.* 2022), and now having populations solely consisting of juvenile plants, renders this species highly exposed to the risk of future fires (Criterion J, Table 9.2). The absence of fire for 20 years or more from areas with recruits will maximise the probability that sufficient seed accumulates to support self-replacement or population expansion after a future fire (Barrett and Yates 2015; Gosper *et al.* 2022).

New populations discovered as part of post-fire field surveys

The slender myoporum or weeping boobialla (*Myoporum floribundum*) (Fig. 9.4) is a shrub recognised as Endangered in Victoria. The species is known from only a handful of populations, most consisting of only a few plants, in the upper catchment of the Snowy River. It

Fig. 9.4. Slender myoporum, taken on the Ingeegoodbee Track, north-east of Suggan Buggan, in early 2022. (Photo: Andre Messina)

represents a species with many data gaps, so its vulnerability was difficult to assess after the fires (Gallagher 2020). A post-fire survey in the Snowy River Gorge area turned up a new, substantial population in a severely burnt area (Criterion E, Table 9.2), highlighting the critical importance of field surveys. The new population had ~100 plants, all regenerated from seed and all high above the flood level of the river, indicating that a population existed there pre-fire and had not recruited from flood-transported seed. Cuttings taken are now growing well at the Royal Botanic Gardens in Victoria.

Fire ephemerals emerge, increasing population size and extent

The Endangered sub-shrub *Androcalva rosea* is a short-lived species once thought to have a highly restricted distribution in the Hunter Valley, NSW. It was known only from four small populations in previously burnt scrubby heath on infertile sandstones, and it was postulated that this species may respond positively to fire (Bell and Copeland 2004).

New populations in their thousands were discovered 30 km away following a fire in 2013 in parts of northern Wollemi National Park that had remained unburnt for up to 70 years (Bell and Holzinger 2015). These plants had evidently germinated from soil-stored seed after decades of fire absence. After the 2019–20 fires, further new populations were uncovered, increasing again the species' known total population size and geographical extent (Bell and Woolley 2021). One new stand discovered on private land at Paynes Crossing proved particularly significant and established a new eastern limit. Although only several hundred plants were present here, this population lay 60 km from the nearest previously known occurrence of the species. Targeted surveys for *A. rosea* conducted around 18 months after the 2019–20 fires have resulted in a significant boost to the number of individuals and populations of this species, and dramatically increased its known geographical range.

The Endangered dwarf kerrawang (*Commersonia prostrata*) (Fig. 9.5) provides another example of how post-fire surveys can be important for locating populations of fire-ephemeral species. Dwarf kerrawang is an elusive species, generally only appearing for a few years following a disturbance such as fire or flood. Prior to the 2019–20 fires, in Victoria this species had only been recorded west of Bairnsdale in the Holey Plains and Providence Ponds areas. However, a small population of this ground-hugging shrub was observed on the banks of the Genoa River during post-fire surveys. This represents a range extension of some 200 km to the east of the known Victorian populations and links them to populations further north in New South Wales and Queensland.

The closely related genera *Androcalva* and *Commersonia* have demonstrated remarkable fire responses following the 2019–20 fires. As well as *A. rosea* and *C. prostrata* noted above, two extremely rare species in Victoria, *C. breviseta* and *C. pannosa*, known from one (1989) and three (1850, 1950 and 1952) herbarium collections respectively, were rediscovered during surveys in 2021 and 2022. Furthermore, a species never previously recorded

Fig. 9.5. A new population of dwarf kerrawang was found in Victoria in post-fire surveys. (Photo: Andre Messina)

in Victoria, *C. rugosa*, was collected in 2021, very near the occurrence of *C. prostrata*. These responses reflect deep 'hard-wired' relationships within this group, suggestive of their evolution in high fire frequency periods, probably millions of years ago.

Cyphanthera scabrella, a shrub species known from only five sites in the Blue Mountains in New South Wales, and largely unseen since 1979, was listed as a high priority after the 2019–20 wildfires (Gallagher 2020). It has been found since in two moderately burnt sites, with more than 600 individuals located. Curiously, a simultaneous survey located 20 mature adults at a site more than 30 km away which was not burnt in the 2019–20 fires and where the plant was last recorded in the 1970s. This discovery may be because they had been previously overlooked, because above-average rainfall in 2020–21 germinated some of the soil seed bank, or perhaps because the thick smoke that blanketed the entire Blue Mountains during the 2019–20 fires provided a germination cue for the buried seed (Commander et al. 2008), including in plants outside burnt areas (Ghebrehiwot *et al*. 2011).

Although the examples described above show the potential for substantial recruitment in post-fire landscapes, the interaction between fire and other threats can jeopardise these gains. For instance, early post-fire surveys of the Critically Endangered Megalong Valley bottlebrush (*Callistemon megalongensis*), known from just one location with ~2000 individuals, found that it was regenerating vigorously by both resprouts and seedlings. However, follow-up visits in March 2020 revealed severe herbivory (Criterion C, Table 9.2) and a substantially reduced population, and fencing was quickly installed to exclude grazing animals and feral pigs. Intense rainfall and subsequent flooding have since led to ongoing erosion adjacent to population that now poses additional threat (Criterion I, Table 9.2). This confirmed the high-risk status assigned after the fires, but, given the substantial data gaps for the species, also highlights the importance of a precautionary approach to post-fire vulnerability assessments and the importance of repeat visits.

For some species it is still too soon to say whether they will ultimately benefit or decline as a result of the fires. Some have had mass seedling germination post-fire, e.g. *Boronia imlayensis* (~160 000 seedlings) and *Kardomia prominens* (~24 000 seedlings), but, with almost all these populations now existing as juveniles, the plants remain extremely vulnerable to disease, herbivory and future fires. These species cannot be considered to have recovered until these recruits have reached maturity and are replenishing the seed bank.

Tales of unburnt species

The importance of investment in long-term monitoring of threatened species can be highlighted by four species that did not burn, even though they were (or were thought to be) in the fire footprint. *Euphrasia bella*, *Coronidium telfordii*, *Olearia* sp. Henrys Creek and *Grevillea bemboka* were initially assessed as having between 7% and 100% of their known occurrences burnt in the 2019–20 fires (Gallagher 2020). All are narrow range endemic species and typically occur in topographically complex environments such as cliff tops and gullies. Limitations inherent in mapping fire boundaries contributed to some unreliability in the initial assessment of fire overlap for these taxa, but assessment of fire overlap was also constrained by the limited availability of accurate location data for occurrences.

The first of these, Lamington eyebright (*Euphrasia bella*), is a perennial herb that occurs in the MacPherson Ranges on the New South Wales/Queensland border, where it is restricted to exposed sites on cliff edges near cool temperate rainforests and in low heathland on rock pavement. During the 2019–20 fires an estimated 68% of its known records were burnt, primarily in Queensland (Threatened Species Operations 2020). However, populations thought to be burnt in New South Wales were found to be incorrectly georeferenced and so not located in the fire footprint. Similarly, records in Lamington National Park were not burnt at all, and while fire mapping does indeed show locations with records in Mt Barney National Park that were burnt, the rainforest that covers the peaks where the species occurs meant that fire was only of low severity.

This is in some ways a good outcome for these species, as they were prioritised for survey based on available information. However, the implications for species that may have been impacted, but were not surveyed, is concerning. Inaccuracy is symptomatic of all species occurrence databases – and considerable ongoing resources are needed to maintain verified and reliable data.

Assessing multiple species by focussing on ecological communities

The Bendethera shrublands (NSW)

This ecosystem occurs on small limestone outcrops deep in the ranges of south-eastern New South Wales. The shrublands comprise an almost continuous thicket of Bendethera wattle (*Acacia covenyi*), with hakea (*Hakea eriantha*), bracelet honey-myrtle (*Melaleuca armillaris*) and blackthorn (*Bursaria spinosa*) occurring as subdominants. The ground cover is sparse and herbaceous.

The ecosystem's structural features are not conducive to the spread of low-intensity fire. In fact, the shrublands have remained unburnt since extensive wildfires in 1969 and several adjacent low-intensity fires have self-extinguished on the boundaries. There was therefore no risk of decline as a consequence of high fire frequency. Instead, the 2019–20 fire event was well timed to initiate regeneration of the shrublands which were in a state of senescence.

The area experienced severe and prolonged drought before the 2019–20 fires (Criterion A, Table 9.2). The high severity of the fire (Criterion E, Table 9.2) reinforced the dominance of the Bendethera wattle because serotinous seed banks of hakea were entirely consumed, while those of honey-myrtle survived only on individuals located within large rock outcrops. Conversely, high fire severity dramatically reduced populations of native and introduced herbivores (Criterion C, Table 9.2) and promoted extremely high rates of germination of Bendethera wattle, which caused a dramatic reduction in the size of the seed bank from an estimated 574 (± 190) seeds/m^2 to below the level of detection. The ecosystem is therefore vulnerable to decline if future fires occur before seed banks are replenished (Criterion J, Table 9.2).

In the immediate aftermath of the 2019–20 fires, these shrublands experienced rainfall estimated to be in the range of 100–200 mm over a 24-hour period. This initiated extensive erosion of topsoil (Criterion I, Table 9.2). On the steeper slopes, which comprise up to one-third of the extent, topsoil loss was associated with much lower densities of seedlings than in other areas.

K'gari (Fraser Island)

K'gari Great Sandy National Park in southern Queensland is an iconic World Heritage area. In November 2019, 12 600 ha at the southern end of the island burnt, and from October to December 2020 a wildfire burnt 85 000 ha in the north. A survey conducted in April 2021

(Neldner and Ngugi 2021; Fig. 9.6) compared the condition of the post-fire vegetation to benchmark values. Thirty sites were permanently marked and sampled in nine regional ecosystems. Most of the vegetation burnt comprised eucalypt woodlands, *Melaleuca* open forest, heathlands and peat swamps, and these all showed a remarkable resilience to the fire with no obvious loss of species and substantial vegetative regeneration occurring on many burnt individuals. There was very limited burning in the *Syncarpia hillii, Lophostemon confertus* open forests or rainforests. The fire varied in intensity, and proportion of tree deaths ranged widely but high intensity fire caused widespread death of trees. In some burnt areas, recovery was characterised by mass germination of *Acacia penninervis* var. *longiracemosa*, *A. flavescens* and *Dodonaea viscosa* subsp. *burmanniana* into dense layers.

Across the 19 sites with data from previous sampling in 1995–2005, the post-fire vegetation appears to contain a similar species composition to that recorded from 1995 onwards. These conclusions are largely consistent with those of Meiklejohn *et al*. (2021) and showed that robust recovery is occurring across all of the nine regional ecosystems sampled, apart from the coastal *Casuarina equisetifolia* subsp. *incana* woodlands and *Banksia integrifolia* woodlands on the frontal beach ridges and high dunes. In this latter vegetation, the death of most adult trees and subsequent lack of regeneration of the dominant tree species, despite adequate follow-up rainfall in these areas, is a major concern.

Recommendations

The 2019–20 fires were likely a harbinger of the types of fire seasons that will become more common due to climate change (Chapter 2). Planning for managing plant species diversity into the future will require strategies and actions taken before, during and following severe fire seasons. Planning should involve all relevant authorities, community members, and Indigenous groups, and be tenure-blind. Several of these recommendations require significant and ongoing investment in resources. The costs involved must be traded off against the savings associated with enhanced conservation of plant diversity that is the foundation

Fig. 9.6. Burnt *Casuarina equisetifolia* subsp. *incana* low woodland illustrating standing dead trees on coastal dune near Happy Valley, K'gari. (Photo: V. John Neldner)

of ecosystems across Australia. The alternative is an *ad hoc* reliance on event-driven funding to support emergency recovery action.

Pre-fire actions

- Manage existing and emerging threats such as fragmentation, disease, invasive weeds, grazing, altered hydrology and climate change to increase resilience and reduce risk from fire events (Monks *et al*. 2019; Gallagher *et al*. in press).
- Increase representation of species and populations in *ex situ* conservation. For species with highly restricted distributions or threatened status, the strategic creation, expansion and monitoring of translocated insurance populations or *ex situ* germplasm collections can contribute to long-term persistence and support future recovery actions.
- Enhance databases of species occurrence to allow for more robust assessments of overlaps with future fires and to help protect important populations.
- Improve understanding of species responses to fire. More than 8000 species-level observations of fire response (e.g. whether they can resprout after fire, have fire-cued recruitment, seed bank longevity, and the length of time after fire until plants first reproduce) have been made in Australia (Falster *et al*. 2021). However, this only represents approximately one-third of Australian plant species. A systematic national program for documenting, collating, or robustly predicting the fire response of plant species is urgently needed to ensure emergency response planning accurately captures impacts.
- Develop and implement fuel management plans to protect highly fire-sensitive populations. Fuel management (e.g. planned fire or mechanical slashing) is routinely undertaken in Australia with the aim of reducing the severity of wildfires and to increase opportunities for fire suppression. For some sensitive plant species, expansion of strategic fuel management to enhance protection of significant plant populations, with integration into broader fuel management plans, may enhance population persistence with future fires. However, the conservation risks of conducting or not conducting strategic fuel management should be subject to careful assessment. Indigenous approaches to burning may be locally helpful (McKemey *et al*. 2021) but also need to be assessed for how these align with the appropriate fire regime for a species, and the risk of adding more fire in a system where climate change is driving increased fire frequency.
- Improve forecasting of the risk of fire. Better prediction of which regions are at risk of fire may improve the capacity to organise and respond to fires. Recent advances have been made in modelling and monitoring spatio-temporal dynamics of fuel conditions, aided by satellite imagery and aerial LiDAR (Price and Gordon 2016; Yebra *et al*. 2013). There are considerable opportunities to improve monitoring and forecasting of fuel conditions by adopting these new technologies into formalised assessments of bushfire risk. Forecasting of other disturbances, in particular drought impacts on vegetation, will also improve risk assessments of plant vulnerabilities to fire.

During fire

Responding rapidly to an emerging fire threat is critical for preventing or reducing negative impacts on some vulnerable plant populations. The capacity to respond both rapidly and effectively during fires will be improved by strategic planning in the years and months preceding a severe fire season.

- Provide information for decision making. Mapping of species occurrences and threats is crucially important for rapid assessment of species vulnerability during fire events.

This mapping also needs to identify priorities for action (i.e. supported by information on species traits, conservation status, and time since last fire), identify what fire-fighting actions are permissible where, for example 'go' or 'no-go zones' for constructing fire breaks, and be readily accessible in a format that is easy to interpret during fire emergencies. Critically, decisions involving priority plants need to be integrated into emergency response frameworks.

- Enhance coordination. Often different agencies, or groups within agencies, are responsible for managing threatened species and for managing fire emergencies. Species may also occur across multiple state and territory jurisdictions that have different statutory responsibilities for management. Clear communication and coordination between and within agencies are vital to ensure that the people deciding where to focus fire suppression efforts have accurate information on the location of high priority species.
- Ensure availability of adequate resourcing and capacity. Responding during a fire event requires adequate resourcing and capacity (Legge *et al*. 2022). Demonstrated effectiveness of strategic and highly targeted fire suppression efforts for flora conservation (e.g. Hannam 2020) indicates that continued investment in capacity and bolstering operational experience in biodiversity-focused fire suppression may yield significant conservation benefits.

Post-fire actions

Post-fire responses are largely characterised by managing interacting biotic threats, such as weeds, disease or herbivory, and, less often, abiotic threats such as erosion. Threats such as climate change and short fire intervals require strategic long-term planning to allow effective management.

- Enhance coordination of strategic post-fire recovery actions. Effective management of interacting threats will be improved by coordination among government agencies, across jurisdictions, and with the community. Community groups are often well placed to undertake post-fire interventions, such as fencing and weeding (e.g. Kohout *et al*. 2020). Monitoring and testing the effectiveness of these actions is critical.
- Implement active restoration of areas where species are at high risk of local extinction. The 2019–20 fires had major impacts on the ash-type forests, where the dominant species are 'obligate seeders' (Clarke *et al*. 2015), and as such at risk of local extinction if fire recurs before flowering and seed-set occurs. Within Victoria, ~30% of the 83 000 ha of ash-type forests that burnt were immature (Nolan *et al*. 2021). In response, the state government initiated the single largest reseeding program to aerially sow seed in these areas (Nolan *et al*. 2021). The success of such initiatives will be dependent on the availability of sufficient seed collected before fire, the resources to conduct such operations, and exclusion of fire until the planted trees have had sufficient time to become reproductively mature.

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