THE EXTENT AND SEVERITY OF THE MACKAY HIGHLANDS 2018 WILDFIRES AND THE POTENTIAL IMPACT ON NATURAL VALUES, PARTICULARLY IN THE MESIC FORESTS OF THE EUNGELLA-CREDITON AREA

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During an unprecedented fire season in Queensland in 2018, a complex of fires burnt in the Mackay Highlands region of Queensland. Some of these fires had been burning continuously since August, but an extreme heatwave in November caused the rapid expansion of intense fire, just prior to the wet season breaking. The fires affected 12 areas of Queensland Parks and Wildlife Service (QPWS) managed estate, with approximately 71,000 ha or 41% of this estate burnt. In this paper, we document the methods used to map the extent and severity of these fires and consider the potential impacts on natural values, within QPWS managed estate. Extensive areas (57,113 ha) of eucalypt woodlands and forests were burnt. Whilst fire adapted, the extent of fire and the high proportion burnt at very high to extreme severity in these ecosystems are likely to have affected a range of significant species. Of particular concern was the area (11,217 ha) of rainforest and scrub communities burnt, particularly cloud rainforests in the Eungella-Crediton area. These are highly fire-sensitive ecosystems and our observations suggest that, even at very low fire severity, impacts are likely highly significant and long lasting. This event provides an important opportunity to assess in detail the ecological effects of fire to inform conservation management of these fire-sensitive communities. With the predicted increases in the frequency, magnitude and duration of heatwaves, fires will become more common within mesic vegetation communities hitherto considered self-protected from fire.

Keywords: Mackay Highlands, Eungella, fire, severity, ecological impact, rainforest

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INTRODUCTION

The 2018 fire season in Queensland was unprecedented. The fire-weather conditions (extreme temperatures, low humidity and strong westerly winds, coupled with preceding dry conditions), particularly during November 2018, led to fire behaviour at an intensity and scale never before seen in the State. This included a catastrophic fire-weather day on 28 November 2018 (BoM, 2018; QFES, 2019).

The extensive Mackay Highlands 2018 wildfire event comprised multiple fires, some burning continuously from August, that culminated with a rapid expansion of intense fire in mid–late November fuelled by extreme fire-weather conditions. Of particular conservation management and ecological significance, the Mackay Highlands fires burnt fire-sensitive upland rainforest, including cloud rainforests, generally regarded as self-protected from fire due to their occurrence on rocky substrates, moist microclimate, or both. Fires were also extensive and at times severe in eucalypt fire-adapted communities.

Here, we summarise the climatic conditions leading up to and during the fire event, describe the extent and severity of the burnt area, document significant species and ecosystems within the burnt area, and discuss possible ecological effects on them. We focus

on the significant natural values of the rainforest and scrubs, and wet eucalypt open forest communities of the Eungella-Crediton area.

MATERIALS AND METHODS

Study Area

This paper reports on the fires that burnt along the Great Escarpment of eastern Australia, from the Mount Hector–Bloomsbury area in the north, to the Blue Mountains area west of Koumala in the south (Figure 1). The major landscape features in this region are the uplands of the Clarke, Connors, Denham, Blue Mountains and Pisgah Ranges, which include many peaks in excess of 700 m altitude. The peaks of Mts David, Dalrymple and William on the Clarke Range within Eungella National Park (NP) rise to above 1200 m in altitude. The region also includes the spectacular formations of Diamond Cliffs, Sydney Heads, The Marling Spikes and Mount Britton in Homevale NP and Resources Reserve (RR). Landforms vary from rolling hills to steeply dissected mountains and valleys. The western slopes of the area drain predominantly into the headwaters of the Burdekin River, with southern areas draining into the headwaters of the Fitzroy River. Many short streams drain the eastern escarpment, including the Pioneer and O'Connell Rivers.

Much of the burnt area falls within the Clarke-Connors Ranges Province of the Central Queensland Coast Bioregion (Young, 1999) which is predominantly subcoastal ranges and uplands, with the highest, moistest parts of the bioregion, generally with a steep eastern fall. Geology is predominantly Carboniferous-Mesozoic granite, diorite, granodiorite, but also Permian volcanics. Vegetation is dominated by notophyll rainforest, *Eucalyptus* open forest and tall open forest. Most of Homevale NP and RR and the western part of Eungella NP fall in the lower-altitude, much drier Bogie River Hills Province of the Brigalow Belt Bioregion. Vegetation in these areas is dominated by open *Eucalyptus* and *Corymbia* woodlands with scattered vine thickets (Young *et al*., 1999).

Climatically, the area of interest typically has marked wet summers and dry winters with median rainfall in excess of 650 mm (BoM, 2019), with upland areas very much moister due to orographic and cloud-stripping effects. Lower areas fall within the hot humid summer climate zone, with elevated areas falling within the warm humid summer or warm summer, cold winter climate zone (BoM, 2019).

Weather Conditions Leading Up to and During the Fire Event

The fire season in the Mackay Highlands area typically comprises the drier months from May to November. The latter part of the 2018 fire season was exceptional, with an extreme heatwave developing during late November. A deep low to the east of southern New South Wales directed a hot and dry westerly airflow across Queensland. Persistent, high to extreme daytime temperatures, combined with very high overnight temperatures and low humidity, created a broad-scale severe to extreme heatwave over and near the tropical Queensland coast from 23 November (BoM, 2018; QFES, 2019). The monthly mean temperature in Mackay for November 2018 surpassed the long-term average mean (29.6°C) by almost 3°C (at 32.5°C), equalling the highest monthly mean on record at 32.5°C (Mackay Aerodrome 1950–2018, BoM climate data online). The average mean temperature for each other month of 2018 exceeded the long-term mean by 0.2°C to 3°C (Figure 2). Compounding higher temperatures, monthly total rainfall for Mackay was below average for each month of 2018 except for April with 166.2 mm, just 2 mm above the long-term average.

For the cloud rainforests of the Eungella-Crediton area, dry conditions were likely significantly exacerbated by the lack of occult precipitation (precipitation that does not get recorded in standard rain gauges, from deposition of cloud, fog or drizzle water onto vegetation, sometimes referred to as cloud stripping: Bruijnzeel, 2001; Holwerda *et al*., 2010) during this period. Typically, these areas are subject to moist afternoon sea breezes that result in cloud or fog forming and sitting on the mountains and escarpment, but this did not occur due to the dry westerly airflow. This not only reduces moisture reaching the forest floor via cloud stripping, but the increase in solar energy accelerates the hydrological cycle and increases evapotranspiration (Cardenas *et al*., 2017), causing further drying of the forest. Temporal and spatial limitations of weather data for the Mackay highlands precludes more specific analyses of climatic conditions leading up to and during the event, especially for upland rainforests. The arrival of the wet season during the first week of December 2018 suppressed the fires.

Assessment Methodology

Given the extent and severity of the Mackay Highlands fires within Queensland Parks and Wildlife Service (QPWS) managed estate, QPWS undertook a post-fire

risk assessment, in more detail than standard for the organisation (Brooke *et al*., 2019). The methods used were modified from those of the Victorian *Bushfire Rapid Risk Assessment Teams* (e.g. DSE, 2009; DEPI, 2014, Case Study 4) and the New South Wales Parks and Wildlife Service and Australian Capital Territory Parks and Conservation *Burned Area Assessment Teams* (BAAT, 2013). The assessment provides QPWS with a snapshot of the priority risks to values, following the fires, to guide short-term responses and to inform long-term recovery planning. Only impacts on natural values are reported here, with the fire event recognised as also having social, cultural and economic consequences.

FIGURE 1. Map of the Mackay Highlands area, showing areas of QPWS estate and NAFI 2018 fire scar mapping. Base map: QTopo.

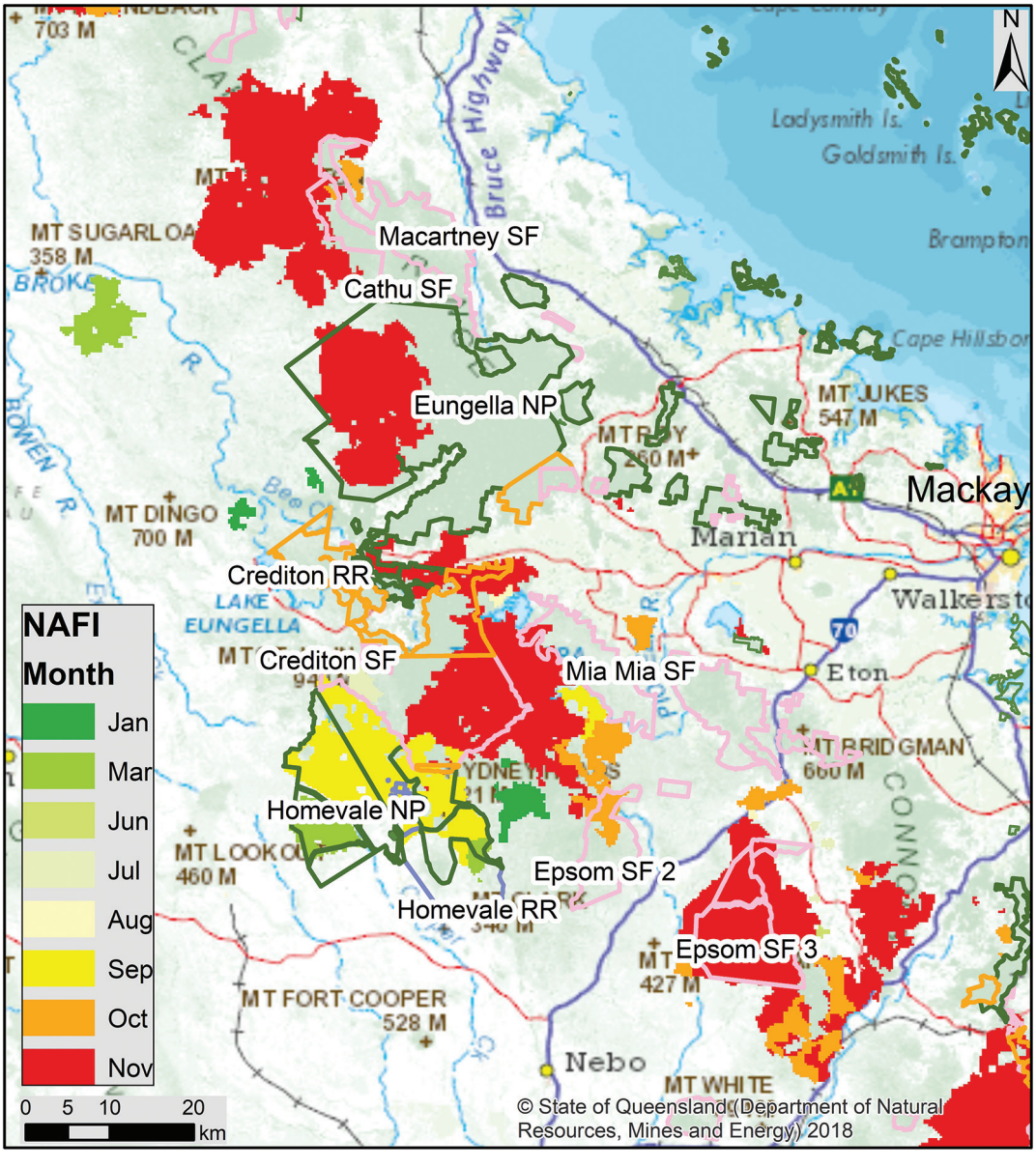
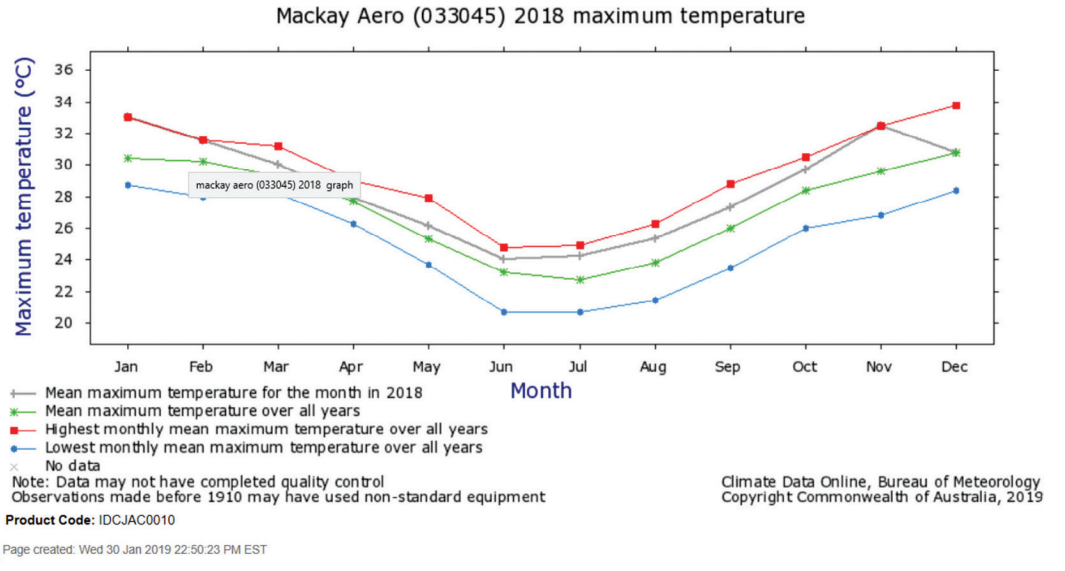


FIGURE 2. Graph of mean maximum temperature, Mackay Aero, for 2018.
Temperatures during 2018 are plotted in grey and are consistently higher than the long-term mean plotted in green, with record temperatures reached in January, February and November 2018.



The assessment on natural values was based on fire extent and severity mapping, distribution of significant natural values with respect to burnt areas, field inspections, published and unpublished information, and expert opinion. The assessment team included local QPWS staff involved with fire suppression efforts and highly knowledgeable of the area, augmented by regional and centrally located natural resource managers and ecologists, a rainforest botanist from the Queensland Herbarium, and regional Queensland Fire and Emergency Service staff. Fieldwork was limited to visual assessments of a range of sites principally in the Eungella-Crediton area, but also included aerial inspections of a broader area. The significant wet season following the fires meant the majority of the field assessments was undertaken in April 2019. The results presented in this paper arose from this assessment.

Fire Extent and Severity Mapping

The Mackay Highlands 2018 wildfire event comprised multiple fires, some burning since August 2018, culminating with a rapid expansion of intense fire in mid–late November that coincided with extreme fire-weather conditions and ending when the wet season broke in early December. North Australia and Rangelands Fire Information (NAFI, 2019) broad-scale fire scar mapping shows the extent of areas burnt by month for 2018 (Figure 1). Early fires (i.e. before August), mostly planned burns, are relatively small in extent. Wildfires became extensive during September, with some reduction in fire activity in October due to rainfall. Fires that started in November, or were already burning, expanded rapidly and show by far the greatest extent of NAFI fire scars for the region in 2018.

We developed finer-scale fire extent and severity mapping as part of the assessment process, using Sentinel 2 satellite imagery that has a resolution of approximately 30 m. Fire severity was determined from pre- and post-fire imagery (for the Homevale area the comparison was 3 September and 8 October, and other areas 3 September and 2 December 2018). A Normalised Burn Ratio (NBR) classification was developed for both pre-fire and post-fire images (Brewer *et al*., 2005; Miller & Thode, 2007). An NBR difference product (dNBR) was derived from the pre- and post-fire NBR classifications and divided into five severity classes, defined as:

extreme = partial to total defoliation, all understorey burnt to ash (or nearly so);

very high = extensive canopy scorch, partial defoliation, no humus remaining;

high = some canopy scorch, mid stratum completely scorched or nearly so, some humus remains;

moderate = little or no canopy scorch, some elevated fuels scorched, some patchiness, 50% humus remains; or

low = little or no canopy scorch, some elevated fuels scorched, significant patchiness, humus layer remains.

These classes were verified through visual interpretation of the imagery and through aerial and ground-based field assessment.

Other Spatial Datasets

Information on significant species was derived principally from the state's wildlife information system, WildNet (accessed 8 May 2019), which includes plant species locality information held by the Queensland Herbarium. Additional species records were collated from the frog survey and monitoring datasets described by Meyer *et al*. (this issue), the QBERD ecological database managed by the Queensland Herbarium (only records not incorporated within WildNet), and the *Atlas of Living Australia* for *Saproscincus eungellensis* and *Magmellia luteilateralis*. Databases were searched for records with a locational precision of 20,000 m or less that fell within the latitudes of –20.676583 and –21.540028, and longitudes of 148.389472 and 148.811000. This rectangle included an approximate 2 km buffer on the northern, eastern, southern and western extent of the QPWS estate affected by the 2018 fire event. Limited spatial validation of these records was undertaken, with some records rejected due to very poor spatial precision, erroneous georeferences, or because they were duplicates. We scored species according to their dependence on forest ecosystems, and some, such as wading birds, were excluded from further consideration. To help identify those threatened forest species most at risk from wildfire, we classified each according to their known or likely fire sensitivity, or dependence upon fire-sensitive ecosystems (Hardesty, 2005). Spatial datasets on significant species are inherently limited and biased, so we used published and unpublished information, as well as expert opinion to augment the spatial assessment and inform the risk-assessment process. Taxon nomenclature and legislative status is from the Queensland Government's wildlife information system, WildNet, as at May 2019.

Regional Ecosystems (REs) are vegetation communities in a bioregion that are consistently associated with a particular combination of geology, landform and soil. The Queensland Herbarium has mapped REs throughout Queensland, and we used the current version (11.1) for this assessment (Queensland Herbarium, 2019). Many areas have a high spatial diversity of vegetation communities, so at 1:100,000 scale it is not always possible to delineate each vegetation community into homogenous (pure) polygons. Consequently, mapped RE polygons are often heterogeneous, such that a polygon is attributed more than one RE code (e.g. 11.3.2/11.3.25), with the percentage of the area of the polygon occupied by each RE or vegetation recorded (Neldner *et al*., 2019a). For the purposes of this report the RE assessment utilises RE1 or the dominant RE for each mapped polygon, and does not attempt to take into account the percentage of it within the polygon. The conservation status of REs used here is the 'biodiversity status' (BD status) (Queensland Herbarium, 2019). REs are grouped into higher-level vegetation communities referred to as Broad Vegetation Groups (BVGs) (Neldner *et al*., 2019b), and we provide some summaries at the 1:2,000,000 and 1:5,000,000 scales, referred to hereafter as 2M and 5M scale.

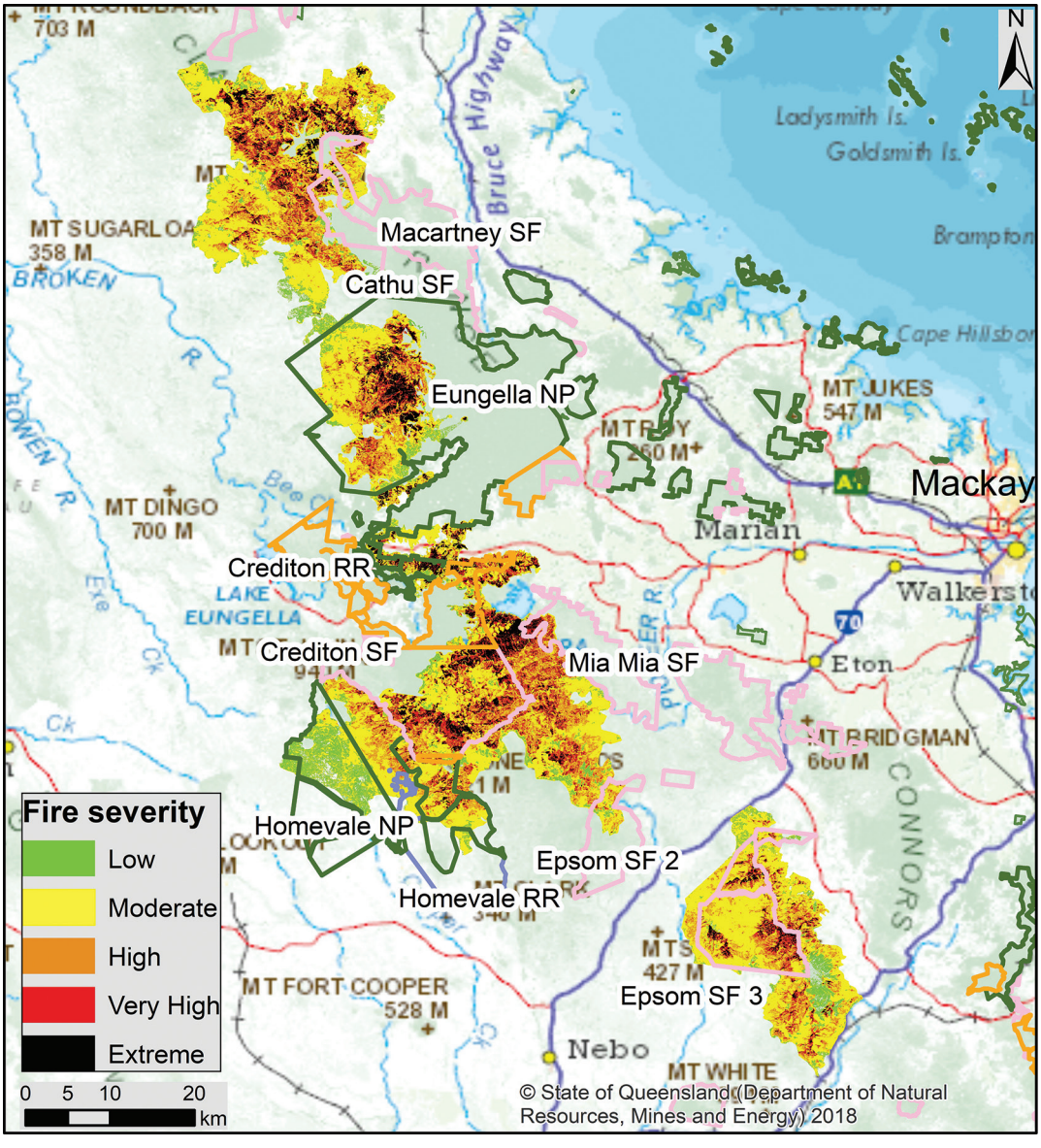
RESULTS AND DISCUSSION

Burnt Area

Overall, the dNBR classification provided a generally reliable assessment of damage to forest canopy reflecting fire severity as assessed from ground truthing. The mapping must be considered an approximation as the analysis and verification was rapid in nature, but it provides finer-scale mapping of extent and severity than other readily available sources (e.g. NAFI). Over the period August–December 2018, fires affected 12 areas of QPWS managed estate (hereafter referred to as burnt QPWS estates) in the Mackay Highlands, with approximately 71,000 ha or 41% of this estate burnt (Figure 3; Table 1). In excess of 10,000 ha was burnt in each of Crediton SF, Epsom SF 3, Eungella NP and Homevale NP. Eungella NP was affected by several wildfires: the largest started on leasehold land to the north-west, and with a hot, dry and strong north-westerly wind, moved south-east into the NP on the afternoon of 12 November 2018. At least two other fires impacted Eungella NP, both burning up from the Finch Hatton lowlands, one to the north and another to the south of Eungella township.

The twelve QPWS burnt estates fall within the Central Queensland Coast and Brigalow Belt Bioregions and support 49 Regional Ecosystems (REs), of which 37 burnt during the event. Of those that burnt with an extent greater than 10 ha, sixteen have a BD status of 'Endangered' or 'Of concern'. Five Broad Vegetation Groups at 5M scale and thirteen at the 2M scale burnt within the QPWS estate (Table 2). At the 2M scale, within QPWS estate, four Broad Vegetation Groups had more than two-thirds of their extent burnt (Table 2).

FIGURE 3. Extent and severity of the Mackay Highlands fire event, August–December 2018, in relation to QPWS estate.



The burnt QPWS estates contain areas of high natural values, in particular the rainforest and scrub communities, wet eucalypt open forests, other eucalypt forest and woodlands and streams. The region is a centre of wildlife endemism, especially within the upland rainforests of the Eungella area. At least 37 threatened or near-threatened species are known or likely to occur within the areas of burnt QPWS estate (Table 3; Figure 4). Of these, seventeen species are fire sensitive (i.e. plant species not dependent on fire for regeneration and killed by low-intensity fire) or are dependent upon fire-sensitive communities (mostly upland rainforests), twelve species are dependent upon fire-prone or fire-adapted communities, and eight species occur within both fire-sensitive and fire-adapted communities. A summary of the extent, severity and observed or inferred effects of the fires within major vegetation communities and their significant species is provided below.

Rainforests and Scrubs

There are fourteen rainforest and scrub REs (mostly evergreen microphyll to notophyll forests) (Group 1, BVG_5M) totalling 58,805 ha within the twelve affected QPWS estates. During the current fire event, 11,217 ha or 19% was burnt, with 3903, 2854, 2138, 1340 and 983 ha at low, moderate, high, very high and extreme severity, respectively (Table 2). Some 4161 ha of rainforest at high altitude (i.e. greater than 800 m asl) was burnt, with approximately a third with high to extreme severity. Rainforests and scrubs are fire sensitive and considered to be generally self-protected, due to their occurrence on rocky substrates or their moist microclimate, particularly the cloud rainforests (mostly above 800 m asl). Field inspections of burnt rainforest in April 2019 showed that even with low flame heights (e.g. 10–20 cm) there was complete loss of leaf litter and ground vegetation (including the seedling bank) and the defoliation or death of vines, shrubs and even very large trees, presumably due to damage to bark and surface roots (Figure 5).

It appears that much of the rainforest that burnt was previously logged. For example, rainforests in the Massey and Pla Creeks catchments were very heavily logged in the 1950–1960s, under the assumption that, post-logging, the remaining areas would be cleared and converted to hoop pine plantations (P. Stanton, *pers. comm.*). The plantations were not established, and the rainforests were left with large canopy gaps that promoted lantana and, more slowly, regrowth of *Alphitonia* and *Acacia* species. Aerial inspection of these areas in early 2018 showed little rainforest canopy recovery and extensive lantana invasion (P. Stanton, *pers. comm.*) which, in combination, likely exacerbated the extent and severity of fire in these areas.

The scrubs and rainforests are core habitat for a range of significant plants and animals, with the cloud rainforests of the Eungella-Crediton area especially important for thirteen species endemic to the Mackay Highlands (Table 3). The significant rainforest plant species are all likely highly fire sensitive, and the loss of individuals from areas of burnt rainforest is almost certain.

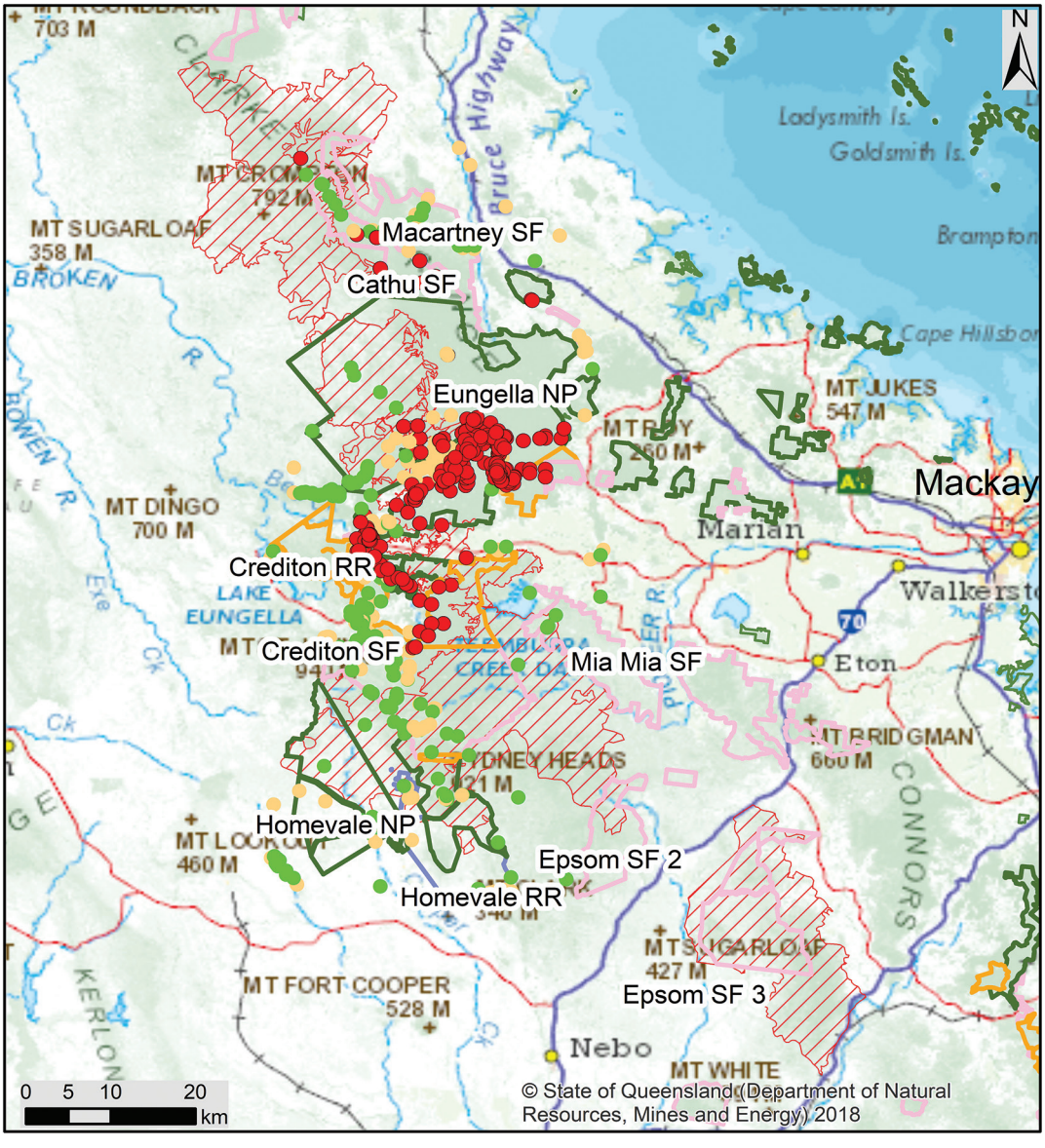
Two terrestrial skinks, *Magmellia luteilateralis* and *Saproscincus eungellensis*, endemic to the upland rainforests of Eungella, are dependent upon large fallen woody debris and leaf litter for shelter and foraging (Wilson, 2015). Direct mortality of these skinks and their prey during the fire is likely, and risk of predation from native and feral predators increased post-fire.

Three species of frogs are endemic to the rainforests of the Eungella-Crediton area: *Rheobatrachus vitellinus*, *Taudactylus eungellensis* and *T. liemi*. *Adelotus brevis* and the regionally significant whirring treefrog, *Litoria revelata*, occur in rainforests as well as other habitats of the Mackay Highlands. The following assessment is based on information from Meyer *et al*. (this issue) and references therein.

TABLE 1. QPWS estate burnt during the 2018 Mackay Highlands fire event.
Estate abbreviations: CP = Conservation Park, FR = Forest Reserve, NP = National Park, RR = Resources Reserve, SF = State Forest.

Estate name	Estate area (ha)	Area of estate burnt (ha)	Percentage of estate burnt
Cathu SF	11,366.0	712.2	6.3
Crediton FR	12,813.0	3,042.1	23.7
Crediton SF	19,562.0	13,408.1	68.5
Epsom SF 1	752.6	514.2	68.3
Epsom SF 2	6,034.0	1,353.6	22.4
Epsom SF 3	10,715.9	10,705.3	99.9
Eungella NP	59,865.4	20,869.0	34.9
Homevale CP	19.5	0.1	0.6
Homevale NP	21,780.6	11,015.0	50.6
Homevale RR	13,300.0	7,355.4	55.3
Macartney SF	7,163.0	1,106.2	15.4
Mia Mia SF	9,000.0	918.7	10.2
Total	**172,371.9**	**70,999.7**	**41.2**

FIGURE 4. Species of conservation significance in the Mackay Highlands area, in relation to QPWS estate and the fire extent (red hatch).
Records of Threatened or Near Threatened species (Table 3) within a bounding rectangle containing the 12 QPWS estates burnt during the Mackay Highlands 2018 fire event. Symbols are: *Fire sensitive* – red dots – species that are fire sensitive (i.e. plants species killed by lower-intensity fire) or are dependent upon fire-sensitive communities; *Fire dependent* – green dots – species dependent upon fire-prone or fire-adapted communities; and *Variable* – orange dots – species that occur within both fire-sensitive and fire-dependent communities.



Taudactylus eungellensis is strongly associated with permanent streams, with their current core habitat comprising larger, boulder-strewn streams at mid-altitude. Direct mortality from the fires is unlikely, as individuals probably took shelter in water or splash zones. Some loss of streamside vegetation may increase predation risk. This species is diurnally active and often perches in very exposed situations,

so likely has adaptations that may limit such susceptibility. The likely greatest impact to *T. eungellensis* is from stream sedimentation/accumulation of burnt debris and short-term changes in water chemistry. An aerial inspection along Massey Creek (April 2019), upstream from about 350 m asl, showed no obvious stream bank instability nor recent build-up of charcoal, silt, sand or gravel, and water was clear. This suggests minimal or transient gross changes to water quality. Tadpoles of *T. eungellensis*, downstream of significant areas of burnt forest, may have experienced significant stress or mortality due to water chemistry changes, which may have reduced recruitment. *Taudactylus liemi* tend to occur in smaller streams, drainage lines and seepages, some of which are more ephemeral and likely dry at the time of the fires. Post-metamorphic frogs shelter in rock piles and leaf litter, including fallen palm fronds. Consequently, this species is likely to have suffered greater direct mortality from the fire. Call perches and breeding sites too are likely to have been directly impacted, with recovery in burnt areas likely to be protracted. Impacts on tadpoles are likely similar to those postulated for *T. eungellensis*. *Adelotus brevis* and *Litoria revelata* are known to forage and shelter well away from streams, so direct mortality from fire is likely. In forests, breeding sites for these species are often pools in bedrock beside streams (e.g. rock holes in cascades or waterfalls, not connected to the stream except during floods) so may not be as susceptible to changes to water chemistry as stream-breeding frogs.

Impacts to frog species of conservation significance are most likely in Massey and Urannah Creeks due to the extent and severity of fire in wet forests in these catchments. However, due to the remoteness of these streams, knowledge of pre-fire distribution and abundance is limited, as is the ability to assess and monitor stream conditions and frog populations post-fire.

In addition to the potential impacts on frogs and skinks outlined above, these species have a diet dependent upon arthropods. Loss of leaf litter, coarse woody debris and standing live vegetation biomass is likely to have greatly reduced arthropod diversity and abundance immediately post-fire.

FIGURE 5. Photographs showing the effects of fire within upland rainforests of the Eungella-Crediton area, ~5 months post-fire (April 2019).

TABLE 2. Area burnt within each fire severity category, by Broad Vegetation Group, within QPWS estate.
Broad Vegetation Groups (BVGs) as described by Neldner *et al*. (2019b), derived from Regional Ecosystem mapping (using RE1). All areas are in hectares. QPWS estate refers to the 12 estates affected by the Mackay Highlands 2018 fire event (see Table 1).
Column headings are: BVG_5M & BVG_2M – descriptions of the BVG at the 1:5,000,000 and 1:2,000,000 scales; Estate – area of BVG_2M within QPWS estate; Burnt – area of BVG_2M burnt on QPWS estate; % burnt – the percentage of BVG_2M within QPWS burnt; Low, Medium, High, Very High and Extreme – area of BVG_2M burnt at these fire severities (see section 3).

BVG_5M	BVG_2M	Estate	Burnt	% burnt	Low	Moderate	High	Very High	Extreme
Non-remnant.	Non-remnant.	4,732.50	1354.55	28.62	724.35	252.42	90.84	71.96	214.97
Rainforests, scrubs.	Complex to simple, semi-deciduous mesophyll to notophyll vine forest, sometimes with *Araucaria cunninghamii* (hoop pine).	813.24	783.55	96.35	655.75	52.85	28.75	20.98	25.21
	Notophyll and mesophyll vine forest with feather or fan palms on alluvia, along streamlines and in swamps on ranges or within coastal sandmasses.	4.27	1.40	32.84	0.00	0.18	0.15	0.39	0.68
	Notophyll to microphyll vine forests, frequently with *Araucaria* spp. or *Agathis* spp. (kauri pines)	50,658.15	9,480.96	18.72	2,837.57	2,578.76	1,953.45	1,208.60	902.58
	Notophyll vine forest and microphyll fern forest to thicket on high peaks and plateaus.	3,215.06	59.80	1.86	14.38	15.52	16.97	9.48	3.45
	Semi-evergreen to deciduous microphyll vine thicket.	4,114.23	892.14	21.68	394.85	206.64	138.70	100.49	51.45
Wet eucalypt open forests.	Wet eucalypt tall open forest on uplands and alluvia.	4,509.63	3,188.07	70.69	297.01	684.73	895.24	598.78	712.31
Eastern eucalypt woodlands to open forests.	Moist to dry eucalypt open forests to woodlands usually on coastal lowlands and ranges.	30,486.44	12,198.94	40.01	958.98	1,555.56	2,909.61	3,664.79	3,110.00
	Corymbia citriodora (spotted gum) dominated open forests to woodlands on undulating to hilly terrain.	29,876.39	18,464.26	61.80	1,945.35	4,657.22	6,054.67	3,821.68	1,985.35
	Moist to dry eucalypt open forests to woodlands mainly on basalt areas (land zone 8).	1,686.00	1,442.54	85.56	1,222.41	212.28	7.08	0.66	0.11

BVG_5M	BVG_2M	Estate	Burnt	% burnt	Low	Moderate	High	Very High	Extreme
Eastern eucalypt woodlands to open forests (*cont.*)	Dry to moist eucalypt woodlands and open forests, mainly on undulating to hilly terrain of mainly metamorphic and acid igneous rocks (land zones 11 and 12).	32,813.92	19,354.85	58.98	6,556.05	6,949.17	4,472.62	1,139.97	237.04
Eucalypt open forests to woodlands on floodplains.	*Eucalyptus* spp. dominated open forest and woodlands drainage lines and alluvial plains.	2,373.79	1,854.46	78.12	209.67	873.81	664.33	94.22	12.43
Eucalypt dry woodlands on inland depositional plains.	*Eucalyptus populnea* (poplar box) or *E. melanophloia* (silver-leaved ironbark) (or *E. whitei* (White's ironbark)) dry woodlands to open woodlands on sandplains or depositional plains.	3,162.01	610.54	19.31	451.89	140.25	18.04	0.35	0.00
	Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains.	27.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Melaleuca open woodlands on depositional plains.	*Melaleuca* spp. on seasonally inundated open forests and woodlands of lowland coastal swamps and fringing lines. (palustrine wetlands).	508.72	163.21	32.08	101.16	28.60	20.36	8.96	4.13
Other acacia dominated open forests, woodlands and shrublands.	*Acacia harpophylla* (brigalow) sometimes with *Casuarina cristata* (belah) open forests to woodlands on heavy clay soils.	538.23	18.56	3.45	8.28	8.68	1.60	0.00	0.00
Other coastal communities or heaths.	Open forests to open woodlands in coastal locations. Dominant species such as *Casuarina* spp., *Corymbia* spp., *Allocasuarina* spp. (she-oak), *Acacia* spp., *Lophostemon suaveolens* (swamp box), *Asteromyrtus* spp., *Neofabricia myrtifolia*.	2,459.91	1,131.39	45.99	67.26	162.11	316.34	290.06	295.62

TABLE 3. Threatened, Near Threatened or endemic forest fauna and flora species of the Mackay Highlands. NCA (*Nature Conservation Act 1992*) and EPBC (*Environment Protection and Biodiversity Conservation Act 1999*) statuses are: EX = extinct, E = endangered, V = vulnerable, NT = near threatened, LC = least concern. Rf & scrub = rainforest and scrubs, Euc = eucalyptus woodlands and forests; with X = the habitat is important for the species in the Mackay Highlands region, End = the species is endemic to the region, and Brig = species occurs in brigalow communities. Eungella spiny crayfish is listed as Critically Endangered on the IUCN Red List.

Group	Common name	Scientific name	NCA	EPBC	Rf & scrub	Euc
Animals						
crustaceans	Eungella spiny cray	*Euastacus eungella*			End	
insects	pale imperial hairstreak	*Jalmenus eubulus*	V		Brig	
amphibians	tusked frog	*Adelotus brevis*	V		X	X
amphibians	northern gastric brooding frog	*Rheobatrachus vitellinus*	E	EX	End	
amphibians	Eungella dayfrog	*Taudactylus eungellensis*	E	E	End	
amphibians	Eungella tinkerfrog	*Taudactylus liemi*	NT		End	
birds	red goshawk	*Erythrotriorchis radiatus*	E	V	X	X
birds	glossy black-cockatoo (northern)	*Calyptorhynchus lathami erebus*	V			X
birds	squatter pigeon (southern)	*Geophaps scripta scripta*	V	V		X
birds	Eungella honeyeater	*Bolemoreus hindwoodi*	V		End	End
birds	powerful owl	*Ninox strenua*	V			X
mammals	northern quoll	*Dasyurus hallucatus*	LC	E	X	X
mammals	ghost bat	*Macroderma gigas*	E	V	X	X
mammals	koala	*Phascolarctos cinereus*	V	V		X
mammals	northern greater glider	*Petauroides volans minor*	V	V		X
mammals	grey-headed flying-fox	*Pteropus poliocephalus*	LC	V	X	X
reptiles	common death adder	*Acanthophis antarcticus*	V			X
reptiles	ornamental snake	*Denisonia maculata*	V	V	Brig	
reptiles	orange-speckled forest-skink	*Magmellia luteilateralis*	V		End	
reptiles	peppered-belly broad-tailed gecko	*Phyllurus nepthys*	LC		End	
reptiles	Eungella shadeskink	*Saproscincus eungellensis*	V		End	
Plants						
Aspleniaceae		*Asplenium normale*	V		End	
Asteraceae		*Ozothamnus eriocephalus*	V	V		X
Dryopteridaceae		*Dryopteris sparsa*	V		X	
Dryopteridaceae		*Elaphoglossum callifolium*	NT		X	
Euphorbiaceae	Mt. Coolum bertya	*Bertya sharpeana*	NT			X
Euphorbiaceae		*Omphalea celata*	V	V	X	
Euphorbiaceae		*Trigonostemon inopinatus*	V		X	
Lamiaceae		*Plectranthus graniticola*	V		End	End
Lycopodiaceae		*Phlegmariurus tetrastichoides*	V	V	X	

Group	Common name	Scientific name	NCA	EPBC	Rf & scrub	Euc
Plants (*cont.*)						
Lycopodiaceae		*Phlegmariurus varius*	V		X	
Myrtaceae	black ironbox	*Eucalyptus raveretiana*	LC	V		X
Myrtaceae		*Kunzea sericothrix*	E			End
Myrtaceae		*Sannantha papillosa*	E			X
Orchidaceae		*Chiloglottis longiclavata*	NT			X
Poaceae		*Dichanthium setosum*	LC	V	X	X
Rutaceae		*Acronychia eungellensis*	NT		End	
Sapindaceae		*Sarcotoechia heterophylla*	NT		End	
Solanaceae		*Solanum francisii*	LC		End	

The Eungella honeyeater (*Bolemoreus hindwoodi*) is also endemic to the region. Higgins *et al*. (2001) summarise the scant published information on this species. Its habitat is predominantly upland rainforests, but it also utilises eucalypt forests and woodlands (possibly more so in winter). The few breeding records are from upland rainforests in spring. Its diet consists of nectar, fruit and insects. Impacts from fires on *B. hindwoodi* are likely to be significant and long term in areas of burnt upland rainforests. Even at low severity, fires killed extensive areas of rainforest climbers of the genus *Freycinetia*, an important food source for *B. hindwoodi*. The species will also be affected where fires burnt at higher severity in eucalypt communities of the Eungella-Crediton area. Impacts will occur over a greater area, but are likely to be much shorter lived as these communities are fire adapted.

Other Fire-sensitive Communities

We estimate that 19 ha of endangered (BD status) brigalow community burnt within QPWS estate (Homevale RR), mostly at low to moderate severity. This vegetation is fire sensitive, although the dominant species – brigalow (*Acacia harpophylla*) – typically resprouts from rootstock, and occurs in lower-altitude, drier areas in the western part of the study area. The pale imperial hairstreak (*Jalmenus eubulus*) is dependent upon brigalow-dominated, old-growth open forests and woodlands (Eastwood *et al*., 2008). This butterfly has been recorded from the region but is patchily distributed, and it is not known whether a population occurred within the burnt area. If present, however, impacts are likely significant. The ornamental snake *Denisonia maculata* also occurs in brigalow communities and has been recorded from the study area, so may have been impacted by the fires.

Wet Eucalypt Open Forests

There are two significant wet eucalypt open forest (Group 2 BVG_5M) REs (*Eucalyptus grandis* and *E. montivaga* communities), with a limited distribution in the higher-elevation western ridges and slopes of the Clarke Range. Both are naturally restricted in occurrence, are only represented in protected areas within Eungella NP and Crediton FR, and have a BD status 'Of concern'. These communities provide important habitat for several threatened species (see discussion below) or important disjunct populations.

RE 8.12.4, *E. grandis* open forests of wet uplands on Mesozoic to Proterozoic igneous rocks (predominantly granite), is threatened by the development of a rainforest understorey and requires fire to prevent this occurring (Bradford, 2018; Queensland Herbarium, 2019). Most areas have been logged, with resulting reduction in size and form of canopy trees. Logging, grazing and, potentially, past fire management have exacerbated weed invasion, with lantana (*Lantana camara*) a particular concern. During the current fire event, 2281 ha (69% of the total extent of this RE within QPWS estate) was burnt, with 272, 486, 615, 449 and 459 ha burnt at low, moderate, high, very high and extreme severity, respectively. During field inspections, we observed mixed-age stands of *E. grandis* in several areas, with recruitment presumably from past fire or logging events, and germination from the current fire event. Defoliation or death of rainforest and lantana shrubby understorey was widespread within the burnt areas visited, with significant fire incursion into some adjacent rainforest stands. The ecological outcomes for this community are likely mixed. Of concern is the extent of fire within this community, with a majority of areas within QPWS estate burnt. However, fire severity was

mixed, with a significant area (1522 ha or 46% of the total extent of the RE within QPWS estate) of high to extreme severity, likely to meet the ecological requirements of this community where affected by rainforest invasion. The reduction in lantana cover is likely short lived, and the fire may in fact provide opportunities for further lantana invasion. High-biomass grasses do not appear to be a significant issue for this community at present.

Some 908 ha (74% of the total extent of this RE within QPWS estate) of RE 8.12.8, *E. montivaga* open forest on plateaus and ridges of high ranges on Mesozoic to Proterozoic igneous rocks, was burnt. Again, fire intensity varied, with 25, 198, 280, 150 and 253 ha burnt at low, moderate, high, very high and extreme severity, respectively. The recommended fire interval for this community is 10+ years with expected intensity high (Queensland Herbarium, 2019). This community tends to grow on exposed ridges with shallow, relatively infertile soils, so rainforest invasion and weeds are not as significant an issue as with the *E. grandis* community. Ecologically, the current fire event is unlikely to have significantly impacted this community.

Other Eucalypt Forests and Woodlands

Large tracts of drier eucalypt open forests and woodlands (Groups 3 & 4, BVG_5M) within the QPWS estate were burnt during the event (Table 2) – about 54,000 ha, or 54% of its extent within the QPWS estate. These vegetation communities are fire adapted and fire prone. Nevertheless, the extent of the fire, as well as significant areas (28,192 ha) with high to extreme severity, are cause for concern.

These eucalypt communities provide important habitat for many threatened or near-threatened species (Table 3). The endangered shrub *Kunzea sericothrix* is only known from a single location, on Dicks Tableland, within the burnt area. *Sannantha papillosa*, another endangered shrub, is also recorded from the burnt area. Both these shrubs occur within highly fire-prone environments and are likely to be well adapted to fire, but their susceptibility to repeated high-intensity fires is not known. These and some other significant plant species grow in skeletal soils on bedrock, which may have afforded protection from fire for some individuals.

The impact of the fire on significant fauna species of the eucalypt communities is difficult to ascertain, as it will vary depending on their distribution, abundance and ecology within the Mackay Highlands area. The Clarke-Connors Range area supports significant populations of koalas (*Phascolarctos cinereus*) (Melzer *et al*., 2018) and northern quolls (*Dasyurus hallucatus*) (Woinarski *et al*., 2008), and specific information on their likely response to extensive and/or intense fire is provided in the reports (*op. cit*.) and sources cited within them. A brief synthesis of this information is provided below.

Dasyurus hallucatus is a medium-sized, predominantly nocturnal, marsupial carnivore, with insects forming a large proportion of the diet. They breed once a year, with young born mid-year. Young are carried by the mother for 8–10 weeks, then left in a den until they are about five months old. Den sites include rocky outcrops, tree hollows, hollow logs, termite mounds and goanna burrows. As the fires coincided with the period when young are in dens, direct mortality may well have been high given the extent and severity of the fire. Recent studies have suggested that *D. hallucatus* are vulnerable to extensive frequent fires. In a detailed radio-tracking study, the main cause of *D. hallucatus* mortality was predation following extensive fire, due to reduced groundcover. In previous studies in central Queensland (including sites within the current burnt area), there was a clear pattern wherein quolls were absent, or in very low numbers, at sites where fire had been extensive; and most abundant where time since fire was longer, or burnt areas were smaller or patchier (such as areas where large boulders broke up the fire). Post-fire predation is likely exacerbated where cats and foxes are present. A key management recommendation of Woinarski *et al*. (2008) was that fire frequency should be low, and burns patchy and of relatively low intensity. The Mackay Highlands 2018 fire event, in contrast, was extensive and of relatively high intensity.

The Clarke-Connors Range is a significant refuge for *P. cinereus* in Queensland, with inappropriate fire considered a critical threatening process in this region. The risks to *P. cinereus*, and to their habitat, are high if fires occur under unsuitable conditions, such as during severe fire weather or high fuel loads that result in high-intensity fires with associated canopy loss and death of individuals. Canopy scorching results in the loss of food and water for *P. cinereus*. Accordingly, *P. cinereus* were likely significantly impacted during and after the fire event. In addition, the extreme heatwave and preceding low rainfall in spring 2018 are likely to have exacerbated fire impact, forcing individuals to seek refuge in creek beds, tree hollows or at the base of trees, making them more susceptible to the

fire and predation. The stress of the fires and heatwave may also increase disease susceptibility (Dr Alistair Melzer, *pers. comm.*). The scrubs (vine thickets/rainforests) adjacent to eucalypt forests are an important refuge for *P. cinereus*, especially during heatwaves: the fires significantly affected some of these communities (Table 2).

Risk Assessment

The QPWS post-fire risk assessment produced fine-scale mapping of fire extent and severity. When used in conjunction with collated information on significant ecosystems and species from local and expert knowledge and published and unpublished literature, this mapping provides a sound basis for assessing potential impacts of the fire to inform short- to long-term recovery planning.

The Mackay Highlands 2018 fire event burnt 71,000 ha of twelve areas of QPWS estate, within various fire-sensitive and fire-adapted vegetation communities at a range of burn severities. Our field observations suggest that even at low fire severity, ecological impacts on upland rainforests are severe and likely long lived. Within the fire-adapted eucalypt communities, some impacts are likely high due to the extent of the burnt area, as well as the proportion of the area burnt at higher fire severities. Past disturbances, such as clearing, grazing, logging and cyclones, preceding rainfall deficiencies with protracted low humidity and high temperatures, including an extreme heatwave, confound assessment of the ecological impacts of the fires. Likewise, potential, or time to, recovery is dependent upon many factors including the extent and severity of future fires, weather, and interactions with pest plants and animals and diseases. Conditions conducive to invasion by pest plants, in particular high-biomass grasses and lantana, were created by the fires in some areas. Establishment of such weed species can impede regeneration directly through competition and, indirectly, by increasing the frequency and severity of future fires. The key ecological outcomes from the fire event are summarised below.

Eucalypt communities are widespread in the QPWS estate of the Mackay Highlands. They are fire-dependent communities, but their ecological fire requirements vary considerably across the study area (Queensland Herbarium, 2019). Lower, drier forests and woodlands with grassy understoreys require fires at greater frequency than wetter, upland communities. Forests with shrubby understoreys tend to require longer fire intervals but burn more intensely. In some wet eucalypt open forests, periodic fire is required to prevent ecosystem transition to rainforest. Accordingly, ecological outcomes will vary with ecosystem type, as well as the extent and severity of the current and past fire events. Although extent mapping of past fires is available for the QPWS estate, fine-scale fire severity mapping is not. Fire frequency and age class assessments were beyond the scope of the current work but are important for informing ongoing fire management of the QPWS estate. Our assessment of ecological outcomes here is restricted to the current fire event.

Our principal concerns for eucalypt communities lie with the vast extent of the 2018 fires and the area burnt at higher levels of severity. Specific information on the ecology of *Phascolarctos cinereus* and *Dasyurus hallucatus* in the Mackay Highlands strongly suggests that the widespread, high-severity fire, coupled with the preceding rainfall deficit and extreme high temperatures, is likely to have had serious impacts. Similar impacts are likely for a range of other fauna in this area for which we lack detailed ecological knowledge. In contrast, at the wetter end of the eucalypt forest spectrum, the 2018 event is likely, in places, to have met ecological requirements. For example, in areas of the 'Of concern' *Eucalyptus grandis* community, the fire appears to have killed rainforest understorey species, opened up the forest structure and, as we observed, initiated recruitment of *E. grandis* (see Stanton *et al*., 2014; Russel & Franklin, 2018). However, recovery of, or invasion by lantana post-fire in this community may outcompete *E. grandis* seedlings and alter subsequent fire extent and severity. At the landscape scale, the 2018 wildfire event likely promoted some pest plants, particularly invasive, high-biomass grasses, which will likely lead to susceptibility to higher-severity fires in the future. Where weeds are not a concern, fire-adapted plant species will regenerate through seedlings (sometimes *en masse*) or through resprouting, and, for many, fires are critical to their ecology.

Rainforests and scrubs are fire sensitive. Drier rainforest types tend to be more resilient to low-intensity fire, as they often occur adjacent to fire-adapted eucalypt communities and have some adaptive traits to cope with low-severity fire. In contrast, upland rainforests, particularly cloud rainforests, are very rarely dry enough to burn and lack appropriate adaptive traits, so are highly sensitive to fire. Uhl *et al*. (1998) demonstrated that tropical rainforests have structural characteristics that confer resistance to fire. Closed canopies trap moisture and maintain an understorey

with consistently high relative humidity that results in leaf litter and other fuels remaining moist between rainfall events. In their study in Venezuela, Uhl *et al*. (1998) estimated that the understorey only dried to a point where combustion was possible less than one day per year on average. In cloud rainforests, like those in the Eungella-Crediton area, such conditions are likely to be even rarer.

We found that even very low flame heights in rainforests and scrubs resulted in the immediate complete loss of leaf litter and the ground stratum, and widespread tree and shrub defoliation or death, immediately or within the months following the fires. Some resprouting of trees and shrubs was evident five months post-fire in areas with low burn severity. In a post-fire study in lowland tropical rainforest in Queensland's Wet Tropics, Marrinan *et al*. (2005) showed most species had some ability to resprout, but a small, potentially significant group of species was less capable than others. Such differences in responses could lead to longer-term changes in rainforest floristics and structure. Many fire-damaged trees and shrubs, however, are likely to succumb to fungal infection, insect attack, exposure and wind throw (House *et al*., 1998). Long-term monitoring is needed to assess fully tree and shrub mortality. Where fire severity was high to extreme, complete tree and shrub mortality is likely, as is total loss of seed and seedling banks. In such circumstances, recovery will be dependent upon immigration of propagules from unburnt rainforest. Rainforest species differ widely in fruiting phenology, dispersal ability and germination requirements. Proximity to unburnt patches will influence rate of recovery, with recovery of the interior areas of large burnt patches likely only in the very long term (100s of years).

Invasion of pest plants, such as lantana or high-biomass grasses, which are prevalent in the Mackay Highlands, will impede recovery. Higher fire severities were particularly evident in rainforests previously disturbed by clearing, logging or road construction, especially where weeds were present. These disturbances open up rainforest, alter microclimate (to become drier and warmer), and lead to changes in floristics (e.g. presence/dominance of *Alphitonia* and *Acacia* species, lantana), which in combination appear to increase flammability.

Future fires within recovering burnt rainforest, particularly where fire-adapted weeds establish, will result in the loss of these communities – as occurred in a patch of complex notophyll vine forest in the Crediton area that burnt in November 1992 (House *et al*., 1998) and November 2018. Logging before the 1992 fire created a discontinuous canopy in places and facilitated the establishment of lantana. An area of 520 ha of the rainforest burnt under extreme fire-weather conditions in 1992, with the majority having greater than 50% crown death. House *et al*. (1998) studied the patch for four years and reported varying levels of recovery dependent upon past logging and fire intensity. They also noted an increasing dominance of lantana. Without further fire, they predicted recovery might take a century or more. The fire in 2018 occurred under severe to extreme conditions and resulted in almost complete replacement of the rainforest with weeds (e.g. *Desmodium uncinatum*, *Lantana camara*, *Parthenium hysterophorus*, *Themeda quadrivalvis*, *Solanum* spp.) apart from some common rainforest pioneer species (Figure 6).

The response of significant fauna species dependent upon rainforest will vary according to their ecology. Loss of ground cover will have significant impacts on species dependent upon it for shelter or foraging (e.g. the vulnerable skinks), or on species with a diet reliant upon arthropods that depend upon forest litter or understorey plants (e.g. potentially stream-breeding frogs). Rainforests burnt at high to extreme fire severity are unlikely to support populations of significant fauna species in the short to medium term. Species dependent upon streams, such as threatened frogs and the Eungella spiny cray (*Euastacus eungella*), may have been subjected to changes in water chemistry and quality following the fire, but the magnitude and extent of these changes (spatially and temporally) or the effect on these species are not known. Some rainforest flora species may benefit from the fires. For example, members of the genus *Solanum* often respond to disturbance, so the endemic *S. francisii* may proliferate in the short to medium term.

In all burnt communities, the risk of predation rises immediately post-fire, due to loss of cover, potentially exacerbating impacts from feral predators such as cats and foxes. McGregor *et al*. (2016) have shown that, in northern Australia, cats will move long distances outside of their home range to forage in recently severely burnt areas, presumably to take advantage of displaced fauna and more open foraging areas.

FIGURE 6. Loss of a rainforest patch in Crediton State Forest due to fires in 1992 and 2018.

CONCLUSION

The Mackay Highlands 2018 fire event burnt extensive areas of fire-adapted and fire-sensitive vegetation communities, some during extreme fire weather. Our assessment has identified a number of likely significant medium- to long-term impacts on the natural values of the region. In particular, recovery of burnt fire-sensitive communities, especially upland rainforests, will take decades to centuries. This event provides an important opportunity to assess in detail the ecological effects of fire to inform conservation management of these fire-sensitive communities. With the predicted increases in the frequency, magnitude and duration of heatwaves (QFES, 2019), fires will become more common within mesic vegetation communities hitherto considered self-protected from fire.

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