Threatened Species Recovery Hub

National Environmental Science Programme




Fire-related risks and conservation strategies for ecological communities

Mark G. Tozer, David A. Keith

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Cover image: (left to right): Top-killed Toona ciliata *and associated vines in Temperate subtropical rainforest at Yattah Yattah Nature Reserve, Milton, NSW; basal resprouting of top-killed* Doryphora sassafras *with* Solanum aviculare *recruitment in Northern cool temperate rainforests at Sassafras, NSW; burnt* Sphagnum cristatum *in Alpine bogs at Delaneys bog, neat Tantangara, Koscuiszko National Park; and vigorous post-fire regrowth of graminoids in Newnes plateau shrub swamp at Budgary swamp, Newnes State Forest, NSW.*

Contents

Executive summary

The black summer bushfires in mainland southeastern Australia during 2019-20 were the most extensive, and among the more severe in recorded history. While the fires burnt a diversity of different ecosystems types, the long-term consequences for ecosystem sustainability are poorly understood, despite potentially far-reaching consequences for biodiversity conservation, cultural values and essential ecosystem services.

To improve understanding of which ecosystem types are affected, how the fires contribute to long term risks and develop risk-reduction strategies, this study applied a diagnostic risk-based approach to rainforests and peat-accumulating ecosystems, two of the most unique and potentially fire-sensitive groups of ecosystems on the Australian continent. We first reviewed available data and developed working classifications to define 14 broad units of rainforest and 11 broad peatland types for national-scale synthesis, in the context of existing listings of threatened ecological communities and jurisdictional classifications. We then developed diagnostic models to identify key ecosystem components, the ecological processes that sustain them, and the threatening processes that underpin risks of ecosystem degradation and collapse.

We found that fire and climate change were pervasive threats across all types of rainforest and peatland. Spatial analyses to quantify the exposure of different rainforest and peatland types to fire-related threats and climate change showed that by 2017, all peatland types and almost all rainforest types are projected to be exposed to more prolonged and more severe drought. Prior to the 2019-20 fires, all peatland types within the study area were exposed to severe and prolonged drought, resulting in fire activity across 50-99% of the distribution of four peatland types and 20-50% of the distribution of one additional type. The proportion of rainforest extent in drought varied from 25 to 100% across different types, resulting in fire activity across 17-88% of their respective distributions.

All ecosystem types have widespread exposure to high-severity impacts from multiple threatening processes (at least three for rainforests, at least two for peatlands). While altered fire regimes and climate change were pervasive, other threats such as habitat loss and fragmentation, invasive plants, vertebrates and disease, nutrient enrichment, erosion, sedimentation and mining-related changes to hydrology were significant threats to particular types of ecosystems.

Based on the threat diagnosis, we developed conservation strategies that bring together a suite of measures primarily to reduce risks associated with major threat syndromes applicable to different groups of exposed and susceptible ecosystems, as well as cross-cutting strategies that support effective governance and implementation. The strategies include measures for protection, threat abatement, management, restoration, research and monitoring, communication and engagement. In addition to these ecosystem-specific risk reduction strategies, all rainforest and peatland ecosystems would benefit substantially from climate mitigation action, which would reduce the severity and extent of ecosystem degradation and the rates of decline.

We make the following recommendations to secure the contributions of Australian ecosystems to biodiversity conservation and human well-being into the future.

- Refine the working typologies for rainforests and peatland ecosystems, by incorporating additional data sources, analyses and expert review, to extend coverage beyond southeastern Australia, develop a finer level of classification within the broadly defined units, and develop detailed descriptions of the units.
- Develop distribution maps for rainforest and peatland types defined in the respective typologies.
- Carry out national-scale risk assessments of rainforest and peatland ecosystems using international standards (IUCN 2016), as adopted in-principle by Australian governments under the Common Assessment Method (CAM) Agreement.
- Implement ecosystem conservation strategies described within this report.
- Extend the diagnostic risk-based approach developed for rainforests and peatlands to the assessment and management of other Australian ecosystem types, including eucalypt forests, heathlands, grasslands wetlands, savannas and deserts.

Burnt rainforest showing top-killed Doryphora sassafras *and with* Calystegia marginata *rapidly climbing up the dead tree trunks and* Solanum aviculare *emerging from soils-stored seed banks, 6 months post-fire. The trees may be killed without fire reaching high in the canopy because their bark is thin and provides poor thermal insulation of sensitive vascular tissues. Sassafras, southern NSW. Image: D. Keith*

Introduction

The 2019-20 bushfires in southern Australia were the most extensive, and among the more severe in recorded history (Boer et al. 2020; Bowman et al. 2020). The effects of these fires, in the context of recent and future fire regimes, on Australian ecosystems are far-reaching in their implications for unique Australian biodiversity, cultural values and essential ecosystem services to rural and urban communities. Australia is one of relatively few nations that has legislative provisions for ecosystem protection and management through the listing of Threatened Ecological Communities (TECs) under the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999* (Keith 2009; Bland et al. 2019). The 2019-20 bushfires have nonetheless highlighted a need to implement well-informed ecosystem management strategies to protect biodiversity and cultural values and sustain ecosystem services for future generations of Australians.

A recent study has identified several direct and indirect mechanisms of bushfire impacts on Australian ecosystems, and a number ecological communities that occur substantially within the 2019-20 fire footprint as candidates for more detailed assessment (Keith et al. 2021). This project focusses on rainforest and peatland ecosystems, which were identified as priorities for detailed assessment by Keith et al. (2021). They are also highly valued and unique ecosystem types within Australia. Their values are recognised in World Heritage Areas and the National Estate, yet they have special vulnerabilities to bushfires. Moreover, their persistence and continuing functionality on the Australian continent appears to be increasingly marginal as changes to climate and fire regimes unfold (e.g. Keith et al. 2014; Kooyman et al. 2020).

The aims of this project are to:

i. diagnose the drivers and mechanisms of ecosystem decline;

ii. assess risks to target ecosystems;

iii. produce condensed conservation strategies to reduce the risks.

We first review and analyse available information to produce working classifications for national-scale syntheses of rainforest and peatland ecosystems in mainland southeastern Australia. We then use these working classifications to address the three aims.

Classification of assessment units

To define the context for this work, we used international (Keith et al. 2020a), national (Keith 2017) and state (refs) classification frameworks of ecosystems and vegetation to review relationships of the identified priority rainforests and peatlands (Keith et al. 2021) with TECs currently listed under the EPBC Act 1999, and with respective finer-resolution units recognised by state environment agencies.

Rainforests

Context

Four major rainforest types are represented in southeastern Australia (Metcalfe & Green 2017) and span four global ecosystem functional groups (Table 1; Keith et al. 2020a). Tropical and subtropical rainforests (T1.1, Keith et al. 2020b) are tall, multi-layered evergreen (typically) closed forests with canopies exceeding 30 m in height. Trees with plank buttresses are common and palms, lianes and epiphytes abundant. Tropical and subtropical lowland rainforests occur in Queensland and New South Wales in areas receiving more than 1200 mm (and up to 8,000 mm) in annual rainfall (Metcalfe & Green 2017). Tropical subtropical dry forests and thickets (T1.2) are simple, closed forests or thickets 10 -25 m in height dominated by mixtures of evergreen or drought deciduous species. These forests occurring in areas experiencing seasonal drought, although annualised rainfall is either in surplus or only small deficits (<100 mm) (Pennington et al. 2020). Lianes are typical but plank buttresses and palms are generally absent. Epiphytes, bryophytes and ferns are common globally but rarely occur in Australian examples (Pennington et al. 2020, Metcalfe & Green 2017). Tropical subtropical dry forests and thickets are found in east of the Great Diving Range in Queensland, Victoria and New South Wales from Townsville to northern NSW, becoming increasing restricted to the coastal hinterland with increasing latitude (Metcalfe & Green 2017). Warm temperate rainforests (T2.4 warm temperate laurophyll forests, Keith et al. 2020c) typically have a relatively simple structure, however Australian examples often exhibit a more complex structure with multiple tree layers (Metcalfe & Green 2017). Lianes, plank buttresses and epiphytes are all rare in these forests, which occur on the coast and adjacent ranges in New South Wales in areas receiving from 1000 – 2000 mm in annual, predominantly summer, rainfall. Cool temperate rainforests (T2.3 Oceanic cool temperate rainforests, Keith et al. 2020d), are structurally and compositionally the least complex of the four major types. They are dominated by one or a few tree species with small leaves, with ferns and mosses the most conspicuous epiphytes and understorey dominants (Metcalfe & Green 2017). They are restricted to high parts of the eastern escarpment of the Great Divide, generally where annual rainfall ranges from 1200 - 3500 mm.

Collectively, the four major rainforest types are represented by at least 250 units in the classification frameworks of New South Wales, Queensland and Victoria (Table 1). Seventeen of these rainforest communities were identified as priority candidates for management and assessment due to putative impacts of the 2019-20 bushfires (Keith et al. 2021.) Six rainforest ecosystems are currently listed as threatened ecological communities nationally under the *EPBC Act 1999*, thirteen are listed in NSW under the *Biodiversity Conservation (BC) Act 2016*, and eight are listed in Victoria under the *Flora and Fauna Guarantee (FFG) Act 1988*. These include examples of almost all major rainforest types represented in southeastern Australia, but it is possible that threats to priority candidates are indicative of syndromes of decline across other compositionally and functionally similar communities.

Synthesis

In order to simplify the diagnosis of threats to rainforest ecosystems for a national synthesis, we developed a working classification using a cluster analysis of floristic samples to aggregate state classification units into broad compositional classes that occupy particular environments and are therefore exposed to common threats.

Vegetation survey data

We leveraged a dataset of 3113 vegetation survey plots sampling rainforest assemblages. Plot sample data were sourced from the NSW BioNet database compiled and administered by the Department of Planning, Industry and Environment (NSW DPIE 2020). We extracted all samples making up the member-sets of Plant Community Types (PCT) nominally attributed by DPIE to the rainforest formation of Keith (2004). These Samples were included in the analysis if their location was recorded with an accuracy of < c. 100 m, the sample area was 0.04 ha and all vascular plant species were recorded in the survey along with cover/abundance estimates. Individual species records were reviewed and modified to resolve inconsistencies in taxonomy (see Methods in Tozer et al. 2010). Taxa identified only at the generic level were excluded from analysis as were naturalised species. Cover-abundance scores were transformed to an ordinal scale with six classes (1 = Uncommon and cover < 5%; 2 = common and cover < 5%; 3 = 5% < cover < 20%; 4 = 20% < cover <50%; 5 = 50% < cover <75%; 6 = 75% < cover <100%). This transformation was chosen to maximise the information content while ensuring compatibility among survey data recorded using different cover/abundance scales.

Previous exploration of similar databases held by the Queensland and Victorian governments, revealed potential inconsistencies with NSW data that may require significant investigation to resolve. Given the limited time available, we limited the scope of this analysis to NSW, where the majority of fire-affected rainforest ecosystems occur. We assumed that rainforests in southeast Queensland and eastern Victoria represent continuations of assemblages identified in adjacent areas of NSW, however further analysis is required to adequately characterise rainforest diversity in those regions for national synthesis.

Definition of assessment units

We diagnosed broad vegetation groups in the NSW data by clustering the floristic plot samples using the Chameleon algorithm (Karypis 1999), a multi-phase clustering algorithm which does not assume clusters conform to a spheroidal model and can adapt automatically the internal structure of the data by combining partitioning and agglomerative phases (Han et al. 2012). Analyses were performed using the CLUTO software version 2.1.2 (Karypis 1999) applying the scluster function operating on pairwise similarity matrices calculated using the Bray-Curtis measure (Kent 2011). We investigated solutions in the range of 15 - 26 clusters to resolve a classification with finer thematic detail than is afforded by the global classification units but substantially broader than the large number of units recognised in the detailed NSW classification (Table 1). We adopted a solution of 15 units generated using graph-partitioning based on a neighbour range at 800 samples. This degree of partitioning corresponded to the limit imposed by the number of non-zero edge-weights and 210 sub-partitions in the agglomerative phase. We identified species diagnostic of the resulting clusters as those with a higher frequency of occurrence within the cluster than across the dataset as a whole (cumulative hypergeometric probability > 0.999) (Tozer 2003). Resemblance among clusters was quantified by computing cluster centroids and calculating neighbour distances based on Bray-Curtis dissimilarity (Clarke 1993). Incidence of exotic species (frequency of specific types, number species per sample) were calculated for each rainforest type.

The inferred relationships of the working units for national assessment to current EPBC and state listings of threatened ecological communities and to the units of respective jurisdictional classifications are given in Table 1.

Sydney sandstone gallery rainforest, an example of a warm temperate laurophyll *forest (see Table 1), with trunk of* Ceratopetalum apetalum *showing a scar from a previous fire. Recurring fires result in tree mortality. Royal National Park, NSW. Image: D. Keith.*

__Table 1.__ Rainforest communities identified by Keith et al. (2021) as priority candidates for assessment (shaded orange) in the context of other rainforests in mainland southeastern Australia, including those currently listed as threatened under Commonwealth (bold) and state legislation (italics). Working units for national synthesis are shaded in blue. Global units are from the IUCN Global Ecosystem Typology (Keith et al. 2020a).

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
T1.1 Tropical and subtropical lowland rainforests				
	Lowland Subtropical Rainforests			
		Lowland Rainforest of Subtropical Australia (EN)		
			Lowland rainforest NSW North Coast and Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3001 Lismore Basalt Subtropical Rainforest
				NSW PCT 3002 Lower Richmond Hills Dry-Subtropical Rainforest
				NSW PCT 3010 Lower Richmond Lowland Hills Dry Rainforest
				NSW PCT 3011 Far North Lowland Subtropical Rainforest
				NSW PCT 3016 Lower Tweed Hills Subtropical Dry Rainforest
				NSW PCT 3062 Coraki Sandstone Rises Dry Rainforest
				NSW PCT 3065 Far North Basalt Gully Dry Rainforest
				NSW PCT 3072 Glenugie Peak Dry Rainforest
				NSW PCT 3093 Mooball Dry Rainforest
				NSW PCT 3109 Southern Lismore Basalt Dry Rainforest
				NSW PCT 3116 Wooloweyah Sandstone Lowland Rainforest
				NSW PCT 3118 Yuraygir Range Gully Dry Rainforest
				NSW PCT 3121 Broken Head Lowland Rainforest
				NSW PCT 4031 Far North Estuarine Swamp Oak Rainforest
				NSW PCT 4110 Lower North Estuarine Sand Dry Rainforest
			Qld RE 12.3.1a (was 12.3.1) Complex notophyll vine forest on alluvial plains	
			Qld RE 12.3.16 (was 12.3.1) Complex notophyll to microphyll vine forest on alluvial plains	
			Qld RE 12.3.17 (was 12.3.1) Simple notophyll fringing forest usually dominated by Waterhousea floribunda	
			Qld RE 12.5.13 Microphyll to notophyll vine forest +/- Araucaria cunninghamii on remnant Tertiary surfaces	
			Qld RE 12.8.13 Araucarian complex microphyll vine forest on Cainozoic igneous rocks	
				Qld RE 12.11.1 Simple notophyll vine forest often with abundant Archontophoenix cunninghamiana (gully vine forest) on metamorphics +/- interbedded volcanics
				Qld RE 12.11.10 Notophyll vine forest +/- Araucaria cunninghamii on metamorphics +/- interbedded volcanics
			Qld RE 12.12.1 Simple notophyll vine forest usually with abundant Archontophoenix cunninghamiana (gully vine forest) on Mesozoic to Proterozoic igneous rocks	
				Qld RE 12.12.16 Notophyll vine forest on Mesozoic to Proterozoic igneous rocks
			Qld RE 12.5.13b Microphyll to notophyll vine forest on coastal remnant Tertiary surfaces	
				Qld RE 12.8.3 Complex notophyll vine forest on Cainozoic igneous rocks. Altitude <600m
				Qld RE 12.8.4 Complex notophyll vine forest with Araucaria spp. on Cainozoic igneous rocks
			Lowland rainforest on floodplain in the NSW North Coast bioregion (NSW EN)	
				NSW PCT 3004 Far North Bangalow Palm Swamp Forest
				NSW PCT 3005 Far North Floodplain Subtropical Rainforest
				NSW PCT 3006 Far North Riverine Bangalow Palm Subtropical Rainforest
				NSW PCT 3007 Far North Lowland Black Bean Riverine Rainforest
				NSW PCT 3012 Far North Waterhousea Riparian Rainforest
				NSW PCT 3015 Lower Richmond Sandflat Subtropical Rainforest
				NSW PCT 3017 Mid North Lowland Floodplain Rainforest
				NSW PCT 3025 Central Coast Gallery Rainforest
				NSW PCT 3059 Clarence Lowland Riparian Red Gum Wet Forest
				NSW PCT 3066 Far North Floodplain Dry Rainforest
				NSW PCT 3089 Lower North Waterhousea Riparian Rainforest
				NSW PCT 3091 Lower North Waterhousea-Water Gum Rainforest
				NSW PCT 3092 Lower Richmond Floodplain Waterhousea Forest

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
				NSW PCT 3102 Northern Lowland Swamp Turpentine Wet Forest
				NSW PCT 3103 Nymboida Water Gum-Myrtle Riparian Forest
				NSW PCT 3104 Richmond Valley Riparian Waterhousea Forest
				NSW PCT 3988 Far North Mesophyll Paperbark Swamp Forest
				NSW PCT 4034 Far North Swamp Oak-Tuckeroo Swamp Fringe Forest
				NSW PCT 3061 Clarence-Richmond Riverine Rainforest
			Qld RE 12.3.16 Complex notophyll to microphyll vine forest on alluvial plains	
			Qld RE 12.3.21 Complex microphyll vine forest on alluvial plains	
		Littoral Rainforest and Coastal Vine Thickets of Eastern Australia (EN)		
			Littoral Rainforest of the NSW North Coast, Sydney Basin and South Coast Bioregions (NSW EN)	
				NSW PCT 3008 Far North Lowland Sub-Littoral Rainforest
				NSW PCT 3122 Far North Littoral Rainforest
				NSW PCT 3123 Far North Sands Coastal Cypress Littoral Rainforest
				NSW PCT 3124 Far North Sands Tuckeroo-Banksia Littoral Rainforest
				NSW PCT 3127 Mid North Headland Brush Box Littoral Rainforest
				NSW PCT 3128 Mid North Littoral Rainforest
				NSW PCT 3129 Mid North Sands Littoral Rainforest
				NSW PCT 3130 Mid North Tuckeroo-Paperbark Littoral Wet Forest
				NSW PCT 3131 Myall-Wallis Lakes Littoral Rainforest
				NSW PCT 3132 Northern Sands Tuckeroo-Banksia Forest
				NSW PCT 3135 Tomaree Headland Littoral Rainforest
				NSW PCT 4113 Far Southeast Littoral Rainforest (part)
				NSW PCT 4114 Lower North Sands Littoral Rainforest
			not listed	Vic. EVC 4 Coastal Vine-rich Forest
			Qld RE 12.2.3 Araucarian vine forest on parabolic high dunes	
			Qld RE 12.2.1 Notophyll vine forest on parabolic high dunes	
			Qld RE 12.2.2 Microphyll/notophyll vine forest on beach ridges	
			Qld RE 3.12.20 Evergreen notophyll vine forest dominated by Welchiodendron longivalve on headlands	
			Qld RE 3.2.1 Evergreen notophyll vine forest in coastal dunefield systems	
				Qld RE 3.2.11 Low microphyll vine forest on coastal dunes and beach ridges
				Qld RE 3.2.12 Araucarian microphyll vine forest on coastal dunefields and beach ridges
				Qld RE 3.2.13 Evergreen notophyll vine forest on beach ridges on the east coast
			Qld RE 3.2.28 Evergreen notophyll vine forest on beach ridges on coral atolls, shingle cays and sand cays	
			Qld RE 3.2.29 Pisonia grandis low closed forest restricted to a few scattered sand cays	
			Qld RE 3.2.31 Premna serratifolia closed scrub on coral atolls, shingle cays and sand cays	
				Qld RE 7.12.11d Low notophyll vine forest and thicket of exposed rocky granite coastal headlands
			Qld RE 7.2.1 Mesophyll vine forest on beach ridges and sand plains of beach origin	
			Qld RE 7.2.2 Notophyll to microphyll vine forest on sands of beach origin	
			Qld RE 7.2.5a Simple mesophyll to notophyll vine forest on sands of beach origin, with Syzygium forte subsp. forte, Buchanania arborescens, Pleiogynium timorense, Dillenia alata, Litsea fawcettiana, and Chionanthus ramiflora	
			Qld RE 7.2.6b Evergreen notophyll vine thicket on aeolian dunes, with Acacia crassicarpa, Elaeodendron melanocarpum, Aglaia elaeagnoidea and Drypetes deplanchei	
			Qld RE 7.11.3b Terminalia arenicola and Acacia polystachya low closed forest on coastal metamorphic headlands	
			Qld RE 8.2.2 Semi-evergreen microphyll vine thicket to vine forest, on coastal dunes	
			Qld RE 7.2.2a Notophyll vine forests, often with Acacia emergents, on dune sands	
			Qld RE 7.2.2b Blepharocarya involucrigera, Atractocarpus sessilis, Choriceras tricorne, Endiandra glauca, Cyclophyllum multiflorum, Syzygium banksii, Polyscias australiana, Terminalia muelleri and Dillenia alata closed scrub to closed forest on dune sands	

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
			Qld RE 7.2.2c Simple notophyll vine forest dominated by Blepharocarya involucrigera on dune sands at sites subject to episodic disturbance or a seral stage of recovery from a single event or period of disturbance	
			Qld RE 7.2.2d Acacia mangium closed forest on dune sands, with A. crassicarpa, Hibiscus tiliaceus, Cupaniopsis anacardioides, Planchonella obovata, Breynia cernua, Morinda citrifolia and Terminalia muelleri	
			Qld RE 7.2.2e Low notophyll vine thicket on transported coastal cobble and boulder ridges	
			Qld RE 7.2.2f Microphyll vine thicket occurring in clumps/groves on coastal foredunes. Inter-grove areas are occupied by sparse grasses and herbs	
			Qld RE 7.2.2g Vine forest with Hibiscus tiliaceus and Calophyllum australianum within intermittently inundated narrow dune swales	
			Qld RE 7.2.2h Semi-deciduous notophyll vine forest on dune sands. Often includes Melia azedarach, Pleiogynium timorense, Ganophyllum falcatum, Falcataria toona, Ficus racemosa, Argyrodendron polyandrum and Alstonia scholaris	
			Qld RE 7.2.1a Complex mesophyll or mesophyll vine forest on sands of beach origin	
			Qld RE 7.2.1b Mesophyll vine forest with Intsia bijuga, Beilschmiedia obtusifolia and Palaquium galactoxylon, on sands of beach origin	
			Qld RE 7.2.1c Closed forest with Calophyllum inophyllum, Terminalia arenicola, Dillenia alata, Myristica insipida, Planchonella obovata, Millettia pinnata and Hibiscus tiliaceus on sands of beach origin	
			Qld RE 7.2.1d Swampy mesophyll vine forest with Archontophoenix alexandrae in the sub-canopy, on sands of beach origin	
			Qld RE 7.2.1e Simple Notophyll vine forest with Syzygium angophoroides, on sands of beach origin	
			Qld RE 7.2.1f Simple notophyll vine forest with Blepharocarya involucrigera, Acacia celsa, Flindersia bourjotiana, Syzygium angophoroides, Dillenia alata, Grevillea baileyana, Syzygium kuranda, Calophyllum sil. Sands of beach origin	
			Qld RE 7.2.1g Mesophyll vine forest with Archontophoenix alexandrae, on sands of beach origin	
			Qld RE 7.2.1h Mesophyll vine forest with Licuala ramsayi, on sands of beach origin	
			Qld RE 7.2.1i Mesophyll vine forest, on sands of beach origin	
			Qld RE 3.2.1a Evergreen notophyll vine forest on coastal dunes and beach ridges	
			Qld RE 3.2.1b Evergreen notophyll vine forest on coastal dunes and beach ridges	
	Upland subtropical rainforest			
		not listed		
				NSW PCT 3003 Border Ranges Black Booyong Subtropical Rainforest
				NSW PCT 3009 Far North Lowland Palm Gully Rainforest
				NSW PCT 3019 Northern Hinterland Baloghia-Booyong Subtropical Rainforest
				NSW PCT 3021 Northern Lowland Subtropical Rainforest
				NSW PCT 3064 Far North Hoop Pine Dry Rainforest
				NSW PCT 3100 Northern Hinterland Baloghia-Dendrocnide Subtropical Rainforest
				NSW PCT 4105 Border Ranges Red Carabeen Rainforest
				Qld RE 12.8.5 Complex notophyll vine forest on Cainozoic igneous rocks.
	Temperate/subtropical Rainforests			
		Illawarra-Shoalhaven Subtropical Rainforest of the Sydney Basin Bioregion (part) (EN)		
			Illawarra Subtropical Rainforest in Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3013 Illawarra Lowland Subtropical Rainforest
				NSW PCT 3078 Illawarra Lowland Wet Vine Forest
			Milton Ulladulla subtropical Rainforest in the Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3013 Illawarra Lowland Subtropical Rainforest
		not listed		
				NSW PCT 3014 Liverpool Range Daphnandra Rainforest
				NSW PCT 3044 Watchimbark Serpentinite Lilly Pilly-Fig Rainforest

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
				NSW PCT 3075 Hunter Valley Rusty Fig Dry Rainforest
				NSW PCT 3086 Lower North Hinterland Riparian Dry Rainforest
				NSW PCT 3097 Northern Escarpment Dry Rainforest
T1.2 Dry rainforests and vine thickets				
	Temperate subtropical Dry Rainforests			
		Illawarra-Shoalhaven Subtropical Rainforest of the Sydney Basin Bioregion (part) (EN)		
			Illawarra Subtropical Rainforest in Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3077 Illawarra Complex Dry Rainforest
			Milton Ulladulla subtropical Rainforest in the Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3077 Illawarra Complex Dry Rainforest
	Subtropical Dry Rainforests			
		not listed		
				NSW PCT 3055 Carnham Dry Rainforest
				NSW PCT 3070 Far North Hinterland Kamala-Coogera Dry Rainforest
				NSW PCT 3080 Killarney Dry Rainforest
				NSW PCT 3099 Northern Escarpment Shatterwood Dry Rainforest
				NSW PCT 3101 Northern Hinterland Shatterwood Dry Rainforest
			Qld RE 12.8.13 Araucarian complex microphyll vine forest on Cainozoic igneous rocks	
			Qld RE 12.8.21 Semi-evergreen vine thicket with Brachychiton rupestris on Cainozoic igneous rocks, usually in southern half of bioregion	
			Qld RE 12.8.22 Semi-evergreen vine thicket with Brachychiton australis on Cainozoic igneous rocks, usually in northern half of bioregion	
			Qld RE 12.9-10.15 Semi-evergreen vine thicket with Brachychiton rupestris on sedimentary rocks	
			Qld RE 12.9-10.16 Araucarian microphyll to notophyll vine forest on Cainozoic and Mesozoic sediments	
				Qld RE 12.11.11 Araucarian microphyll vine forest on metamorphics +/- interbedded volcanics, usually in southern half of bioregion
			Qld RE 12.11.4 Semi-evergreen vine thicket on metamorphics +/- interbedded volcanics	
			Qld RE 12.11.12 Araucarian complex microphyll vine forest on metamorphics +/- interbedded volcanics, usually in northern half of bioregion	
			Qld RE 12.11.13 Semi-evergreen vine thicket on metamorphics +/- interbedded volcanics, usually in northern half of bioregion	
				Qld RE 12.12.13 Araucarian Complex microphyll to notophyll vine forest on Mesozoic to Proterozoic igneous rocks
			Qld RE 12.12.17 Semi-evergreen vine thicket on Mesozoic to Proterozoic igneous rocks, usually in southern half of bioregion	
			Qld RE 12.12.18 Semi-evergreen vine thicket on Mesozoic to Proterozoic igneous rocks, usually in north of bioregion	
	Tablelands and Coastal Rainshadow Valleys Dry RF			
		Western Sydney Dry Rainforest and Moist Woodland on Shale (EN)		
			Western Sydney Dry Rainforest in Sydney Basin Bioregion (NSW EN)	
			Moist Shale Woodland in the Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3110 Greater Sydney Enriched Grey Myrtle Dry Rainforest
				NSW PCT 3082 Western Sydney Complex Dry Rainforest
		not listed	*Lower Hunter Valley Dry Rainforest in the Sydney Basin Bioregion (NSW VU)*	
				NSW PCT 3076 Hunter Valley Whalebone Dry Rainforest (part)
				NSW PCT 3120 Hunter-Peel Ranges Dry Rainforest
		not listed	*Dry Rainforest of the South East Forests in the South East Corner Bioregion (NSW EN)*	
				NSW PCT 4112 Southeast Dry Rainforest

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
		not listed	*Mount Kaputar high elevation Dry Rainforest land snail and slug community (NSW EN)*	
				NSW PCT 4143 Northwest Ranges Alectryon Dry Rainforest
				NSW PCT 4144 Northwest Ranges Fig Dry Rainforest (part)
		not listed	*Hunter Valley Vine Thicket in the NSW North Coast and Sydney Basin Bioregions (NSW EN)*	
				NSW PCT 3119 Upper Hunter White Box Vine Thicket
		not listed	*Brogo Wet Vine Forest in the South East Corner Bioregion (NSW EN)*	
				NSW PCT 3108 South Coast Scarp Wet Vine Forest
		not listed		
				NSW PCT 3079 Kandos Riparian Rainforest
				NSW PCT 3112 Tenterfield Hills Dry Rainforest
				NSW PCT 3113 Timbarra Sheltered Gorges Vine Thicket
				NSW PCT 3114 Upper Hunter Ranges Moist Gully Forest
				NSW PCT 3469 Macleay Gorges Low Scrubby Dry Rainforest
			Dry Rainforest (Limestone) Community (Vic Threatened)	
				Vic EVC 34 Dry Rainforest
	Western Vine Thickets			
		Semi-evergreen vine thickets of the Brigalow Belt (North and South) and Nandewar Bioregions (EN)		
			Semi-evergreen Vine Thicket in the Brigalow Belt South and Nandewar Bioregions (NSW EN)	
				NSW PCT 4145 Northwest Olive-Wilga Vine Thicket
				NSW PCT 4144 Northwest Ranges Fig Dry Rainforest
			Qld RE 11.11.18 Semi-evergreen vine thicket on old sedimentary rocks with varying degrees of metamorphism and folding	
			Qld RE 11.2.3 Microphyll vine forest ("beach scrub") on sandy beach ridges and dune swales	
			Qld RE 11.3.11 Semi-evergreen vine thicket on alluvial plains	
			Qld RE 11.4.1 Semi-evergreen vine thicket +/- Casuarina cristata on Cainozoic clay plains	
				Qld RE 11.5.15 Semi-evergreen vine thicket on Cainozoic sand plains/ remnant surfaces
			Qld RE 11.8.13 Semi-evergreen vine thicket and microphyll vine forest on Cainozoic igneous rocks	
			Qld RE 11.8.3 Semi-evergreen vine thicket on Cainozoic igneous rocks	
				Qld RE 11.8.6 Macropteranthes leichhardtii thicket on Cainozoic igneous rocks
			Qld RE 11.9.4 Semi-evergreen vine thicket or Acacia harpophylla with a semi-evergreen vine thicket understorey on fine-grained sedimentary rocks	
				Qld RE 11.9.8 Macropteranthes leichhardtii thicket on fine grained sedimentary rocks
	Backhousia Dry RF			
		not listed		
				NSW PCT 3034 Northern Gorges Riparian Rainforest
				NSW PCT 3056 Central Eastern Ranges Riparian Dry Rainforest
				NSW PCT 3057 Chaelundi-Carrai Rocky Peaks Myrtle Scrub
				NSW PCT 3098 Northern Escarpment Grey Myrtle Gully Rainforest
				NSW PCT 3106 South Coast Grey Myrtle Dry Rainforest
				NSW PCT 3111 Sydney Hinterland Grey Myrtle Riparian Forest
				NSW PCT 3117 Yarriabini Moist Shrubland
				NSW PCT 3151 Northwest Sydney Sandstone Grey Myrtle Dry Rainforest
				NSW PCT 4111 Lower North Grey Myrtle Riparian Dry Rainforest

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
T1.4 Warm temperate laurophyll forests				
	Sydney Sandstone Gallery RF			
		not listed		
				NSW PCT 3038 Sydney Coastal Coachwood Gallery Rainforest
				NSW PCT 3041 Sydney Sandstone Coachwood-Grey Myrtle Rainforest
				NSW PCT 3043 Upper Blue Mountains Gully Rainforest
	Southern Warm Temperate Rainforest			
		not listed		
				NSW PCT 3024 Blue Mountains Gorge Warm Temperate Rainforest
				NSW PCT 3036 South Coast Warm Temperate-Subtropical Rainforest
				NSW PCT 3045 South Coast Temperate Gully Rainforest
				NSW PCT 3046 Southeast Warm Temperate Rainforest (part)
				NSW PCT 3105 South Coast Escarpment Dry Rainforest
				NSW PCT 4113 Far Southeast Littoral Rainforest (part)
				NSW PCT 3039 Sydney Coastal Lilly Pilly-Palm Gallery Rainforest
				Vic EVC 32 Warm Temperate Rainforest
			Strzeleckis Warm Temperate Rainforest Community (Vic Threatened)	
				Vic EVC 32 Warm Temperate Rainforest
			Warm Temperate Rainforest (Coastal East Gippsland) Community (Vic Threatened)	
				Vic EVC 32 Warm Temperate Rainforest
			Warm Temperate Rainforest (Cool Temperate Overlap, Howe Range) Community (Vic Threatened)	
				Vic EVC 32 Warm Temperate Rainforest
			Warm Temperate Rainforest (East Gippsland Alluvial Terraces) Community (Vic Threatened)	
				Vic EVC 32 Warm Temperate Rainforest
			Warm Temperate Rainforest (Vic Threatened)	
				Vic EVC 32 Warm Temperate Rainforest
			Warm Temperate Rainforest (FarEast Gippsland) Community (Vic Threatened)	
				Vic EVC 32 Warm Temperate Rainforest
				Vic. EVC 135 Gallery rainforest
	Lowland Temperate Rainforest			
		not listed		
				NSW PCT 3040 Sydney Coastal Foreshores Gully Rainforest
				NSW PCT 3039 Sydney Coastal Lilly Pilly-Palm Gallery Rainforest
	Southern Warm Temperate/Subtropical Rainforest			
		not listed		
				NSW PCT 3028 Illawarra Escarpment Warm Temperate Rainforest
				NSW PCT 3037 Sydney Basin Warm Temperate Rainforest

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
	Northern Warm Temperate Rainforest			
		not listed		
				NSW PCT 3031 Northern Escarpment Coachwood-Beech Rainforest
				NSW PCT 3033 Northern Escarpment Sassafras-Prickly Ash Rainforest
				NSW PCT 3048 Border Ranges Antarctic Beech Rainforest
				NSW PCT 3053 Northern Escarpment Sassafras Rainforest
				NSW PCT 4107 Mid North Escarpment Coachwood Warm Temperate Rainforest
				NSW PCT 3026 Comboyne Plateau Warm Temperate Rainforest
				NSW PCT 3035 Northern Ranges Coachwood Warm Temperate Rainforest
				Qld RE 12.8.18 Simple notophyll vine forest with Ceratopetalum apetalum on Cainozoic igneous rocks
T2.3 Oceanic cool temperate rainforests				
	Northern Cool Temperate Rainforests			
		Robertson Rainforest in the Sydney Basin Bioregion (EN)		
			Robertson Rainforest in the Sydney Basin Bioregion (NSW EN)	
				NSW PCT 3047 Sydney Montane Basalt Rainforest
		not listed	*Ben Halls Gap National Park Sphagnum Moss Cool Temperate Rainforest Community (NSW EN)*	
				NSW PCT 3051 Mount Royal Range Cool Temperate Rainforest
		not listed		
				NSW PCT 3046 Southeast Warm Temperate Rainforest (part)
				NSW PCT 3049 Kosciuszko Cool Temperate Rainforest
				NSW PCT 3050 Mount Bajimba Antarctic Beech Rainforest
				NSW PCT 3052 Northern Escarpment Antarctic Beech Rainforest
				NSW PCT 3054 Southeast Cool Temperate Rainforest
				NSW PCT 4106 Illawarra Escarpment Cool Temperate Rainforest
				NSW PCT 4108 Northern Escarpment Rocky Peaks Cool Temperate Rainforest
				Qld RE 12.8.6 Simple microphyll fern forest with Nothofagus moorei on Cainozoic igneous rocks
				Qld RE 12.8.7 Simple microphyll fern thicket with Acmena smithii on Cainozoic igneous rocks
	Southern Cool Temperate Rainforest			
			Cool Temperate Rainforest Community (Vic Threatened)	
				Vic EVC 31 Cool temperate rainforest
			Cool Temperate Mixed Forest (Vic Threatened)	
				Vic EVC 30 Wet forest
				Vic EVC 31 Cool temperate rainforest

Environmental relationships among rainforest assessment units

Differences in the distribution of rainforest types in relation to environmental factors were explored using boosted regression tree (BRT) models. We chose this method over gradient analysis because it yields more direct insights into the environments in which different vegetation types occur and because we anticipated gradients underlying such wide range of vegetation types would be complex and difficult to elucidate in a small number of dimensions. We built individual BRT models for 14 of the 15 units of the rainforest classification (the 15th unit included unclassified samples and was not considered further). Model predictors included five variables representing physical features (elevation, slope, topographic position and roughness, annual solar insolation), eight representing climate variables (annual actual evaporation (AET), AET deficit, AET surplus, annual minimum, maximum and average temperature, average diurnal temperature range, annual average number of days <0°C), distance to depositional features (alluvium, estuarine sediments, barrier sands) and five representing soil properties average over depths 0 – 100 cm (effective cation exchange capacity (CEC), total Phosphorus (P), total Nitrogen (N) and percent sand (S) and clay (C) contents (CSIRO 2021)). We estimated the values of predictors by intersecting sample locations with relevant spatial data layers using a GIS. Spatial layers were derived from terrain models, soil maps or remote-sensed data as described in Appendix S1. Models were fitted in RStudio (Rstudio Inc. 2020) version 1.2.5033) using gbm package version 2.1.8 (Ridgeway 2006) and the BRT functions of Elith et al. (2008). Models were built with tree complexity set at three, holding out 25% of samples for cross-validation. Learning rate was varied between 0.005 and 0.001 to ensure at least 1000 trees were fitted (Elith et al. 2008).

Major compositional rainforest variants are distributed along gradients in temperature and availability represented by actual evapotranspiration (Table 3, Fig. 1). Compositional gradients align with gradients in structural features. Tall, complex and diverse multi-layered rainforests occupy the warmest, most well-watered environments, while both structural and compositional diversity decline with temperature and rainfall. Only temperate subtropical (C8), upland subtropical (C7) and lowland subtropical (C13) rainforests experience significant evapotranspiration surpluses. Only northern warm temperate (C2) and cool temperate (C4) rainforests occur at elevations high enough to permit significant moisture inputs from cloud harvesting (Table 3). Southern warm temperate (C0), Sydney sandstone gallery (C10), *Backhousia* and tablelands and coastal rainshadow dry rainforests all predominantly occur in locations with a high degree of topographic shelter (Table 3). Upland and lowland subtropical (C7, C13), Sydney sandstone gallery (C10), northern warm temperate (C2), lowland temperate (C11), and temperate subtropical (C12) and subtropical dry (C3) rainforests occur in areas with very low incidence of frost (Table 3). Patterns in the distribution of rainforest types in relation to soil properties are more difficult to elucidate from remote-sensed spatial data, however northern warm temperate (C2), upland subtropical (C7) and subtropical dry (C3) rainforests are associated with clay-rich soils with high levels of Phosphorus relative to other rainforest types which occur on soils with higher sand contents (Table 3).

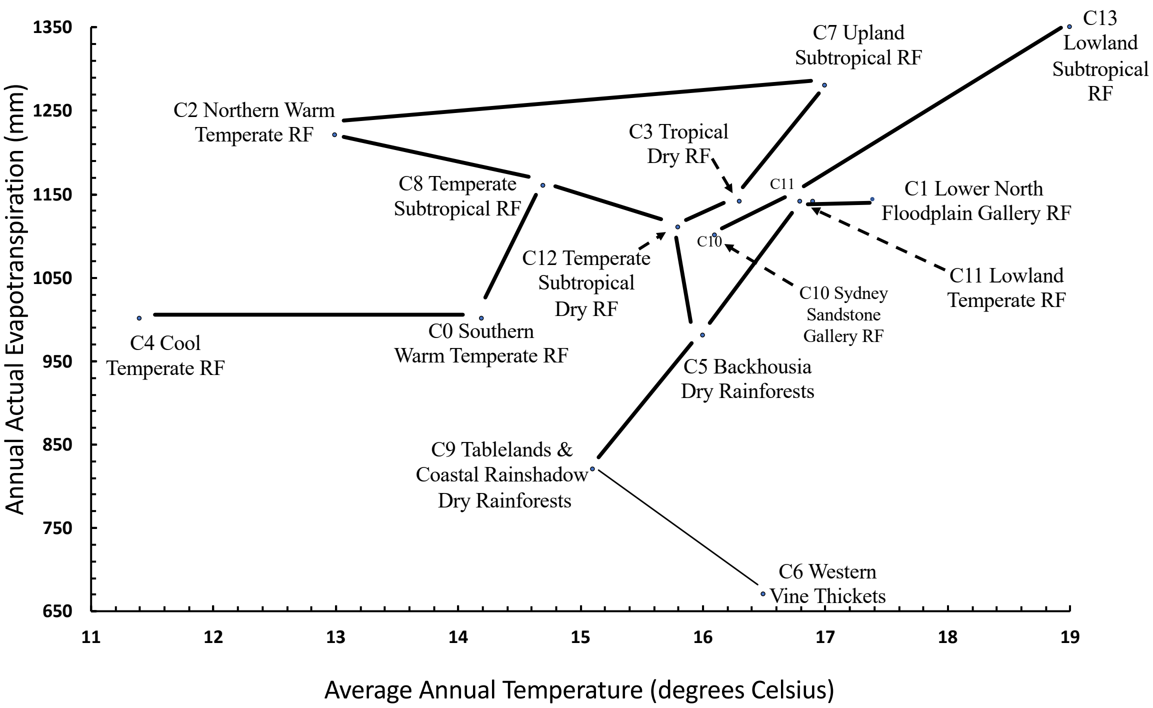

Figure 1. *Compositional relationships between broad rainforest types in relation to gradients in temperature and moisture availability represented by actual evapotranspiration. Solid bars indicate relationships between clusters with the thickness of the bar proportional to compositional similarity between the respective cluster centroids.*

Peatlands

Context

Fire-affected peatland ecosystems (or, strictly, peat-accumulating ecosystems) in southeastern Australia encompass two global ecosystem functional groups (FT1.6 Boreal, temperate and montane peat bogs, and FT1.7 Boreal and temperate fens; Keith et al. 2020a). There is currently no widely used national classification system for peat-accumulating systems in Australia, so we adapted vegetation classes of Keith (2004), recognising three major groupings: 'heath swamps'; 'montane bogs and fens'; and 'alpine bogs and fens'.

Heath swamps are oligotrophic (nutrient-poor) systems with vegetation dominated by sclerophyll shrubs, sedges and cord rushes. They occur primarily near the coast on sandstone plateaus and sandplains (Keith & Myerscough 1993; Griffiths et al. 2003), but may occur over 1000 m elevation on low-nutrient sandstones and leucogranites in the Blue Mountains and New England tableland, respectively (e.g. Benson & Baird 2012).

Montane bogs and fens are mesotrophic systems that vary from acid peats with a mixture of shrubs, forbs, sedges and grasses, to fens that have the highest pH and nutrient levels, and generally lack woody plants (e.g. Hunter & Bell 2009). They occur on elevated tablelands, mostly above 500 m into the subalpine zone.

Alpine bogs and fens experience regular winter snow and may be buried under snow pack for weeks or months, generally above 1500 m elevation on mainland Australia. They include essentially the only truly ombrogenous (rain-fed) bogs in Australia, which are characterised by Sphagnum hummocks, sclerophyll shrubs, forbs, sedges and grasses, as well as more restricted and less diverse eutrophic fens that lack woody plants (Costin et al. 1979).

Synthesis

Ground survey data are currently insufficient to support a quantitative classification of peat-accumulating ecosystems across southeastern Australia. A preliminary classification was therefore derived from a review and interpretation of subregional classifications currently in use within each state and territory jurisdiction, as well as current jurisdictional listings of threatened ecological communities. Across the three major groupings described above, eleven working units were defined as natural aggregations of 55 units defined within state and territory classifications on the basis of qualitative differences in vegetation, substrate and regional distributions (Table 2).

The study area includes three peat-accumulating ecosystems listed as nationally threatened under the EPBC Act 1999, four listed in NSW under the BC Act 2016, and three listed in Victoria under the FFG Act 1988 (Table 2). Three of these were identified as priorities for post-fire management (Keith et al. 2021). The relationships among these listings are complex with EPBC listings encompassing parts of some state listings and all of others, as well as other peatlands not listed at state level. The exception is Coastal Upland Swamp, which is essentially an identical listing under Commonwealth and NSW legislation.

Alpine Sphagnum bog with dense Sphagnum cristatum *with* Astelia alpina *and emergent shrubs of* Richea continentis *and* Epacris paludosa*. Unburnt since c. 1960. Mt Stillwell, Kosciuszko National Park. Image: D. Keith.*

__Table 2.__ Peat-accumulating ecosystems identified by Keith et al. (2021) as priority candidates for assessment (shaded orange) in the context of other peatland systems in mainland southeastern Australia, including those currently listed as threatened under Commonwealth (bold) and state/territory legislation (italics). Working units for national synthesis are shaded in blue. Global units are from the IUCN Global Ecosystem Typology (Keith et al. 2020). National units adapted from Keith (2004) (see text).

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
FT1.6 Boreal, temperate and montane peat bogs / FT1.7 Boreal and temperate fens				
	Heath swamps (oligotrophic)			
		Coastal Upland Swamp (EN)		
			Coastal Upland Swamp (NSW EN)	
				NSW PCT 3925 Sydney Sandstone Button Grass Sedgeland (part)
				NSW PCT 3923 Sydney Coastal Sandstone Creekline Swamp Heath
				NSW PCT 3924 Sydney Coastal Upland Swamp Heath
				NSW PCT 3917 Shoalhaven Lowland Heath
		Temperate highland peat swamps on sandstone (sandstone component) (EN)		
			Blue Mountains swamps (NSW VU)	
				NSW PCT 3894 Blue Mountains Creekline Shrub Swamp
				NSW PCT 3925 Sydney Sandstone Button Grass Sedgeland (part)
				NSW PCT 3928 Blue Mountains Damp Coral Fern Swamp
				NSW PCT 3929 Blue Mountains Swamp Heath
			Newnes Plateau Shrub Swamp (NSW EN)	
				NSW PCT 3945 Newnes Plateau Shrub Swamp
				NSW PCT 3946 Newnes Plateau Swamp Woodland
		not listed	Morton-Penrose sandstone swamps (NSW, ACT Jervis Bay)	
				NSW PCT 3919 Southern Highlands Wet Swamp Heath
		not listed	not listed/Least Concern: Sandplain swale bogs (NSW, Qld)	
				NSW PCT 3900 Northern Sandplain Saw-sedge-Fern Swamp Heath
				NSW PCT 3907 Lower North Sands Swamp Scrub
				NSW PCT 3908 Lower North Sands Wallum Bottlebrush Swamp Heath
				NSW PCT 3911 Northern Sand Swale Fernland
				NSW PCT 3912 Northern Sand Swale Paperbark Sedge Shrubland
				NSW PCT 3913 Northern Sandplain Wet Heath
				NSW PCT 3915 Northern Sands Prickly Tea-tree Wet Shrubland
				Qld RE 12.2.12 Closed heath on seasonally waterlogged sand plains
		not listed	not listed: Clarence sandstone swamps (NSW)	
				NSW PCT 3897 Lower Clarence Sandy Creekflat Sedgeland
				NSW PCT 3899 Clarence Sandstone Plateau Wet Heath
		not listed	not listed: New England granite bogs (NSW)	
				NSW PCT 3934 Eastern New England Granite Wet Heath
				NSW PCT 3937 Northern Escarpment Granitoid Wet Heath
		not listed	not listed: Southeast Corner lowland swamps (NSW)	
				NSW PCT 3901 Far South Hinterland Heath
				NSW PCT 3903 Far Southeast Lowland Heath Swamp
				Vic EVC 53 Swamp Scrub

(Global IUCN GET)	National (working units)	EPBC listed	State listed	Other state units
	Montane bogs and fens (mesotrophic)			
		Temperate highland peat swamps (non-sandstone component; only where indicated* EN)		
			Montane Swamp Complex Community (Vic Threatened)	
				Vic EVC 8 Damp heath
				Vic EVC 318 Montane swamp
			Montane Peatlands and swamps of the New England Tableland, NSW North Coast, Sydney Basin, South East Corner, South Eastern Highlands and Australian Alps Bioregions (NSW EN)	
				NSW PCT 3927 Barrington Subalpine Swamp Meadow
		*		NSW PCT 3932 Central and Southern Tableland Swamp Meadow Complex
				NSW PCT 3936 Ebor Basalt Wet Heath
				NSW PCT 3939 Kosciuszko Western Flanks Wet Meadow
				NSW PCT 3940 Liverpool Range Swampy Tea-tree Shrubland
				NSW PCT 3942 Monaro Creekflat Peat Swamp
				NSW PCT 3948 Southeast Subalpine Bog
		*		NSW PCT 3949 Southern Highlands Sand Swamp Sedgeland
				NSW PCT 3952 Tuggolo Adamellite Montane Heath Swamp
			The following PCTs are transitional between montane peatlands and other ecosystems:	
				NSW PCT 3391 Munghorn Seepage Wet Herbfield
				NSW PCT 3951 Southern Tableland Ranges Boggy Open Woodland
				NSW PCT 3954 Western Central Tableland Upland Swamp
				NSW PCT 3930 Bondo Montane Flats Swamp Woodland
			Carex Sedgeland of the New England Tableland, Nandewar, Brigalow Belt South and NSW North Coast Bioregions (NSW EN)	
				NSW PCT 3944 New England Tableland Carex Fens
	Alpine bogs and fens			
		Alpine Sphagnum bogs and associated fens (EN)		
			Alpine Bog Community (Vic Threatened)	
				Vic EVC 210 Alpine peatland
				Vic EVC 288 Alpine valley peatland
				Vic EVC 1002 Alpine damp grassland
				Vic EVC 1011 Alpine hummock peatland
			Fen (Bog Pool) Community (Vic Threatened)	
				Vic EVC 171 Alpine fen
			High Country Bogs and Associated Fens (ACT EN)	
			not listed	Alpine bogs and fens (NSW)
				NSW PCT 3890 Kosciuszko Alpine Wet Heath
				NSW PCT 3891 Kosciuszko Range Boggy Herbfield
				NSW PCT 3892 Kosciuszko Subalpine Valley Damp Heath
				NSW PCT 3888 Kosciuszko Subalpine Valley Wet Meadow
				NSW PCT 3883 Alpine Short Herbfield
				Sphagnum peatland (Tas Threatened)
				Tas vegetation community MSP Sphagnum peatland

Methods

Diagnosing the drivers and mechanisms of ecosystem decline

To address Aim (i), we synthesised current scientific understanding from peer-reviewed literature, technical reports, available spatial and time series data sets, and expert consultation to produce conceptual models that represent the key drivers and mechanisms of ecosystem decline. The models were presented in diagrammatic format to identify the characteristic biotic components, the ecological processes that sustain them and the major threats.

Assessment of risks to target ecosystems

To address Aim (ii), we employed different approaches for rainforest and peatland ecosystems due to contrasting constraints imposed by the available data. Rainforests presented a more complex assessment than peatlands due to the large number of state-level classification rainforest units and the uncertain relationships among them. Fortunately, they also had a larger number and more comprehensive coverage of ground survey samples available than peatlands, enabling a quantitative analysis to assess their exposure to particular threatening processes. Although fewer ground-data are available for peatlands, their distribution is relatively well mapped because they have distinctive remote sensing signatures that have been well characteristised in regional vegetation mapping programs. We therefore assessed 11 peatland working units (Table 2), using compilations of available vegetation mapping to estimate their exposure to threatening processes.

Threat exposure

We estimated the relative risk posed by fire and drought to different ecosystem types by analysing the exposure of each rainforest and peatland type (see respective working classifications, Tables 1 & 2) to the 2019-2020 fires and to antecedent and projected future drought scenarios. We used the National Indicative Aggregated Fire Extent Dataset (NIAFED) to identify samples within the fireground and a fire severity map derived from Sentinel 2 satellite imagery (Gibson et al. 2020) to estimate the proportional extent of fire within each unit. The incidence of severe drought leading up to the 2019-2020 fires was estimated using the Standardised Precipitation Index (SPI). Locations were categorised as experiencing severe drought at the time of the 2019-2020 fires if cumulative rainfall during the 12 months before December 2019 was more than two standard deviations below the long-term average (McKee et al.1993). Future drought projections were based on CMIP5 global climate model simulations (Kirono et al. 2020). We focussed on projections for Standardised Soil Moisture Index (SSMI) under extreme drought conditions estimated for four drought metrics (percent time spent in droughts, mean drought duration, mean drought frequency, and mean drought intensity) for the year 2070. We intersected plot locations (rainforests) or mapped polygons (peatlands) with relevant spatial data layers representing fire and drought using a GIS then used generalised linear models to characterise: i) differences among types in likelihood of burning given exposure within the fireground; ii) interactive effects between rainforest types and antecedent drought; and iii) differences among rainforest types in terms of exposure to future drought.

Conservation strategies

To address Aim (iii), we prepared condensed conservation strategies for the rainforest and peatland ecosystems assessed as most at risk. The strategies will be designed to reduce identified risks specific to the ECs, focussing particularly on managing fire regimes into an uncertain future, their interactions with other threats and protocols for fire incident responses. As part of strategy development, we will review all existing conservation actions implemented to date for each priority EC. As far as possible we will identify actions that offer generic benefits in risk reduction across a broad suite of ECs, but the scope of this project for review of EC-specific actions and development of EC-specific strategies will be limited to those rainforest and peatland ECs identified as priorities under Aim (ii). We used strategies in Approved Recovery Plans as a template to structure the condensed conservation strategies to ensure that they are a format suitable for direct integration into statutory documents (Recovery Plans, Conservation Advice), and agency operational plans (e.g. NSW Saving Our Species program plans).

Findings

Threat diagnosis (Aim 1)

Rainforests

High primary productivity in rainforests is underpinned by reliable moisture supply founded primarily on annual precipitation surpluses (+ seasonal deficits), supplemented in some montane regions by cloud harvesting, but also on reduced evapotranspiration losses afforded by topographically sheltered locations (Figure 1). Productivity may also be sustained by fertile substrates, although some rainforest types may be found on relatively low-nutrient substrates where much of the nutrient capital resides in the vegetation and is sustained by efficient and rapid cycling. High rainfall produces high rates of leaching, which can rapidly deplete nutrient stocks when the vegetation cover is destroyed (Metcalfe & Green 2017). Rainforest tree canopies are distinctively 'closed' (high Leaf Area Index), and may be multi-layered with a wide range of leaf sizes. Canopy complexity provides habitat for a diverse trophic web including herbivorous and predatory arthropods, some with high dietary specificity, as well as a distinctive bird and mammal fauna, including frugivores that may disperse plant propagules over considerable distances. Canopy tree populations are sustained by gap-phase regeneration, typically from seedling banks that exhibit highly plastic growth rates in relation to deep shade and light gaps created by tree fall. Only a few species have persistent soil seed banks. The dense tree canopies are instrumental to maintaining a moist and heat-reduced microclimate in the understorey and forest floor which, in turn, sustains a shade-tolerant flora and diverse trophic web of microbial, fungal and invertebrate decomposers and detritivores that rapidly cycles the productive leaf fall. The moist microclimate is also critical to maintaining rainforests in low-flammability states, and hence most rainforests rarely burn, with return intervals of many decades or centuries coinciding with prolonged severe droughts, or not at all (Fig. 2).

Rainforest ecosystems are threatened by multiple interacting processes that derive from human activity at global to local scales (Fig. 2). The threats to rainforest ecosystems are diverse, with several syndromes of threat associated with climate change (Fig. 2) including: i) increased frequency and severity of heat waves affecting survival of canopy fauna as well as trees; ii) reduced climatic moisture surplus and increased variability, with increasing severity and duration of droughts reduce survival, growth and reproduction of much rainforest biota, disrupt the moist microclimate and make rainforests more flammable for more time. Rainforests on fertile substrates and flat terrain are especially prone to clearing and conversion to rural land uses. Although, broad-scale clearing of rainforest is largely a historic threat, small-scale clearing for infrastructure, hobby farms and urban development continues, while remaining fragments are subject to legacy effects such as extinction debts, nutrient influx and invasions of exotic plants, herbivores and predators, as well as degradation related to disturbance related to access by people, vehicles and livestock. Invasive diseases, notably myrtle rust reduce diversity of forest canopies and their dependent fauna, even in relatively remote intact areas.

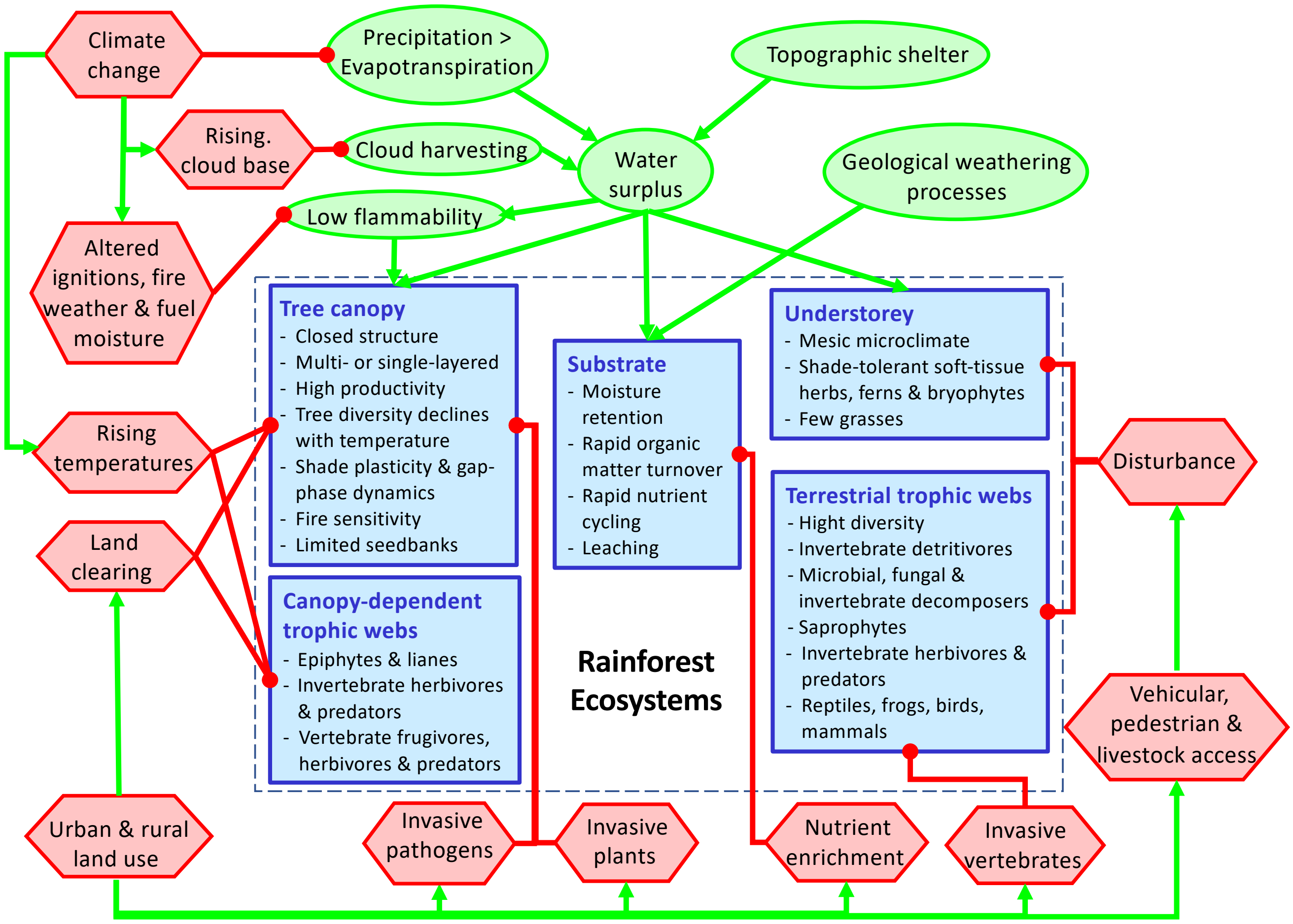

Figure 2. *Major components (blue boxes within the dashed line) of rainforest ecosystems in subtropical and temperate mainland Australia, the critical biophysical processes that sustain their function and diversity (green ellipses) and the threatening processes that disrupt and degrade them through networks of positive (green arrows) and negative (red lines and terminal circles) interactions and effects.*

Peatlands

Peat-accumulating ecosystems in Australia comprise six major components (Fig. 3). The peaty substrates are sustained by periodically high water tables and consequently poorly aerated substrates, which limit microbial activity and the breakdown of plant litter from the standing vegetation. The usually treeless standing vegetation comprises a thick cover of non-woody vascular plants, sometimes with Sphagnum hummocks, other Bryophytes and variable densities of sclerophyll shrubs, which attain greatest dominance and diversity in heath swamps (see commentary on Table 2). The dense standing vegetation reduces surface flows, promoting moisture retention and sediment accumulation in feedback processes that sustain the system. It also supports a diverse array of invertebrate herbivores, granivores and detritivores and their predators in the plant canopies and on the soil surface. The dominant plants are hydrophytes with specialised traits that enable metabolism in low-oxygen substrates (e.g. aerenchymatous tissues, superficial cluster roots). The substrates contain regenerative and proliferating organs, as well as soil seed banks, that are critical to rapid recovery of vegetation after disturbance. They also host stygofauna and burrowing macroinvertebrates (notably crustaceans, dragonflies) that promote bioturbation of the sediments and create refugial shelters for surface fauna including frogs, reptiles, arachnids and other invertebrates. The dense ground vegetation also supports small mammals and scrub birds.

Hydrological processes are critical to the sustainability of peat-accumulating ecosystems (Fig 3). They are generally restricted to climates in which precipitation exceeds evapotranspiration most of the year and in net terms annually. Impermeable baserock layers limit vertical percolation and sustain a perched watertable. Substrates vary from sandstones, siltstones, basic and acid igneous rocks to B-horizons of deep podsols. All Australian peatlands are fire-prone to varying degrees. Surface fires occur in summer months when evapotranspiration allows vegetation to dry sufficiently to carry fire. In many of these systems, sustainable fire regimes (i.e. within tolerable ranges of frequency, severity and season) are critical to maintaining the diversity of the ecosystem biota, by creating gaps for plant recruitment and interrupting elimination of inferior competitors. Peat fires are less common than surface fires, and occur in dry years with peat consumption of varying depth determined by residual levels of substrate moisture content (Pryor et al. 2020). Extreme peat consumption is rare, but known from the stratigraphy of some swamps (Young 2018).

Peat-accumulating ecosystems are threatened by multiple interacting processes that derive from human activity at global to local scales (Fig. 3). Anthropogenic climate change is altering the hydrological budgets of peatlands by reducing the excess of precipitation over evapotranspiration, mainly through increases in the latter. Consequently the bioclimatically suitable habitat for peat-accumulation is projected to contract rapidly in coming decades, although lags may be expected in the ecological response (Keith et al. 2014). Australia is already climatically marginal for development of mire ecosystems. A secondary effect of climate change is through increasing frequency severity and duration of droughts, and increasing incidence and severity of fire weather (Clark et al. 2016), which may push fire regimes beyond sustainable bounds for peatland ecosystems, particularly through increased incidence of severe peat fires (Pryor et al. 2020). The effects of climatic drying are likely to be exacerbated and accelerated by longwall coal extraction beneath peatlands that occur on sedimentary base rocks over coal strata, particularly in the Sydney Basin where impermeable Triassic base rocks overlie Permian coal measures (Table 4). Extraction of the coal seam by longwall methods increases permeability and water loss through cracking of the overlying base rock and surface warping (Mason et al. 2021).

Other major threats to peat-accumulating ecosystems are associated with urban and rural land uses in their catchments (Fig. 3). Disturbance associated with urban development, transport and service infrastructure, plantation forestry, cropping and grazing generates surface erosion and influx of sediments, nutrients and weed propagules via altered surface flows into the wetlands, all of which degrade the diversity and function of the ecosystems (Hose et al.). Intensive land uses may result in clearing of vegetation and drainage works within the peatland, especially on the urban fringe and in farm production landscapes. In livestock production landscapes, such as those on the southern tablelands of NSW (Table 8), repeated incursions of livestock have caused extensive transformation of peatland ecosystems through trampling and browsing, as well as erosion and nutrient influx, resulting in simplification of the biota and dominance by exotic plants. Invasive vertebrate pests, notably horses, pigs and deer have similar impacts, both in rural districts and in remote natural areas where densities are high (ref Driscoll). At more local scales, apparently irreversible impacts occur in less developed areas, including protected areas, where the wetlands are intersected by major roads, access tracks, pipelines and other linear infrastructure. These disrupt stabilising root mats and act as conduits for more rapid surface flow and influx of sediments and nutrients. Unauthorised vehicular, pedestrian or livestock access (e.g. 4-wheel drives and trail bikes), which may be prominent in peri-urban areas, has similar effects (Fig. 3). Finally, urban and rural land uses may have feedback effects on fire regimes by increasing the frequency of unplanned ignitions, hazard reduction burning, grazing management burns, arson, infrastructure incidents and accidental ignitions (Fig. 3).

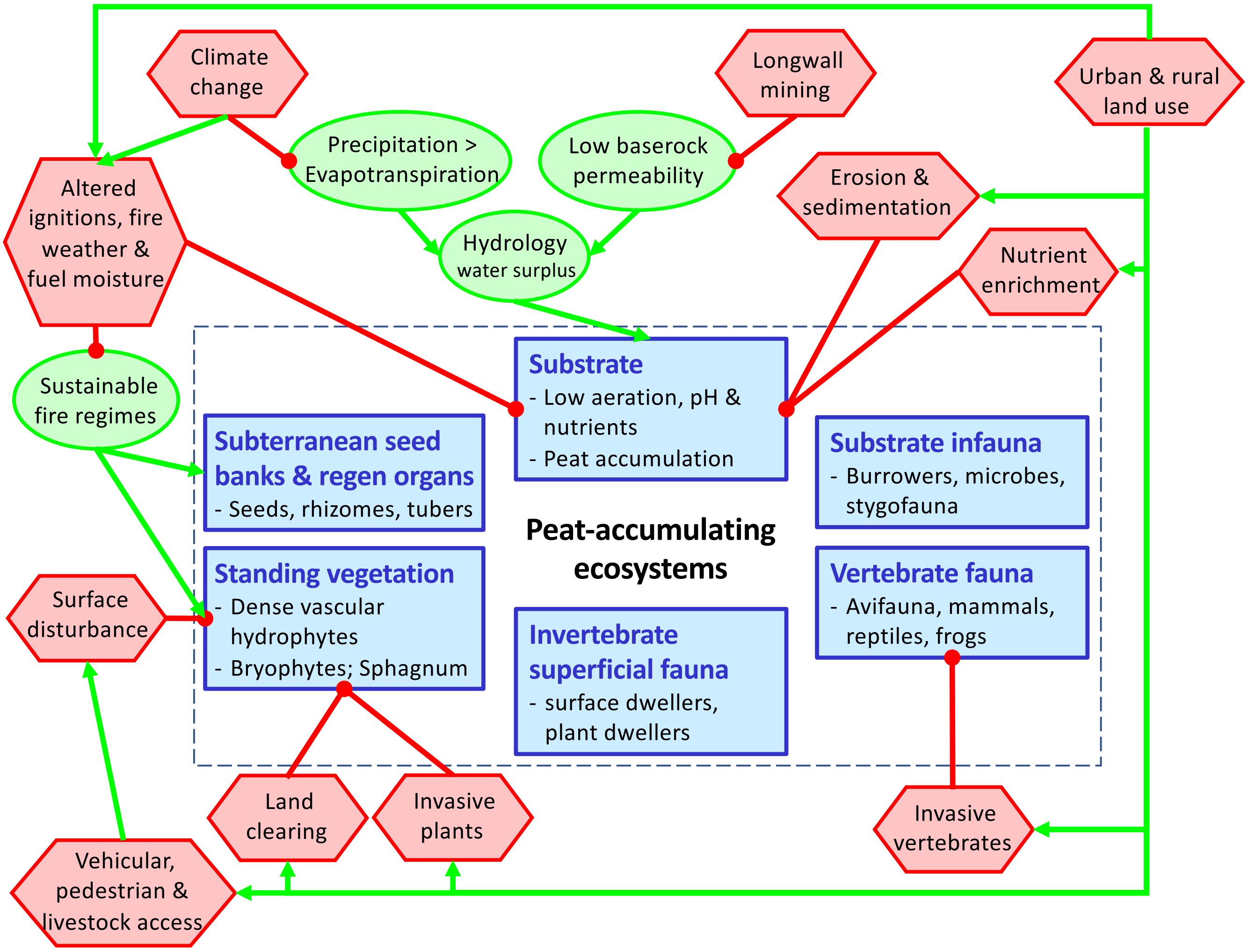

Figure 3. Major components (blue boxes within the dashed line) of peat-accumulating ecosystems in Australia, the critical biophysical processes that sustain their function and diversity (green ellipses) and the threatening processes that disrupt and degrade them through networks of positive (green arrows) and negative (red lines and terminal circles) interactions and effects.

Preliminary risk assessment (Aim 2)

Rainforests

A broad dichotomy exists between the rainforests of the lowlands and those of the rugged hinterland and ranges and corresponds to two broad syndromes of decline (Table 6). Rainforests of the lowlands have been extensively cleared or modified in the transformation to agricultural and urban development since European settlement. Lowland rainforests are the most heavily impacted by processes associated with fragmentation (Laurance et al. 2000, 2006) and associated disturbances such as weed invasion (Table 3), especially those forms that occupy relatively fertile soils. Most of the currently listed rainforest TECs belong to these categories (Tables 1 & 6) and are characterised by high or very high declines in historical distribution. Rainforests of the uplands and escarpment ranges are generally less impacted by human activity at local scales and retain higher proportions of their pre-European distribution although some have been significantly impacted by forestry activities in the past.

New threats, such as disease, fire and climate change are affecting both lowland and upland rainforests. Myrtle rust disease (*Austropuccinia psidii*) is causing rapid declines in canopy and subcanopy trees such as species of *Archirhodomyrtus, Decaspermum, Lenwebbia, Pilidiostigma, Rhodamnia, Rhodomyrtus, Syncarpia, Syzygium* and *Uromyrtus*, and rates of decline are likely to be accelerated after fire as the young post-fire regrowth is more susceptible to the disease (Pegg et al. 2021).

Table 3. Average number of exotic species by rainforest type and frequency of occurrence (% of samples) of the most frequently recorded species.

Rainforest type	Average exotic species/plot	*Lantana camara*	*Tradescantia fluminensis*	*Ochna serrulata*	*Ageratina riparia*	*Senna pendula*	*Asparagus eathiopicus*	*Cinnamomum camphora*	*Bidens pilosa*
Southern Warm Temperate Rainforest (C0)	0.67	4	2	1	0	0	1	0	0
Lower North Gallery RF (C1)	9.1	60	86	2	74	0	0	22	16
Sydney Sandstone Riparian Gallery RF (C10)	2.4	12	12	8	14	6	8	6	3
Lowland temperate RF (C11)	5.05	57	20	23	12	15	27	11	8
Temperate/subtropical Dry RF (C12)	2.39	41	9	4	6	4	2	1	10
Lowland subtropical RF (C13)	4.19	57	5	24	8	30	19	21	6
Northern Warm Temperate RF (C2)	0.04	0	0	0	0	0	0	0	0
Subtropical Dry RF (C3)	0.64	38	1	1	0	0	0	0	0
Cool Temperate Rainforest (C4)	0.18	0	0	0	0	0	0	0	0
Backhousia Dry RF (C5)	1.42	25	4	3	4	0	2	0	5
Western Vine Thicket (C6)	3.62	0	0	0	0	0	0	0	21
Upland subtropical RF (C7)	0.82	13	3	5	3	2	1	5	0
Subtropical/temperate RF (C8)	0.71	9	6	1	7	0	1	2	0
Tablelands and Coastal Rainshadow Valleys Dry RF (C9)	3.33	6	1	0	2	0	0	0	23

Rainforests of all types are vulnerable to anthropogenic climate change, although the mechanisms are varied and almost certainly involve interactions with fire. Reliable moisture availability is critical to the sustainability of rainforest ecosystems, and the area of suitable habitat is therefore likely to contract to those areas where precipitation exceeds evapotranspiration or where deficits can be sustained at modest levels in the face of rising temperatures, reduced rainfall or increasing concentration of annual rainfall in fewer rainfall events. There is some uncertainty surrounding the impacts of changes to hydrological budgets on different types of rainforests, and components of these ecosystems may be differentially affected. For example, given current, significant rainfall surpluses, temperate subtropical (C8), lowland subtropical (C13) and upland subtropical (C7) rainforests may be able to sustain current levels of primary production under conditions of reduced water availability, however processes such as nutrient cycling and aquatic ecosystem components which require abundant moisture may decline, and a greater proportion of species in subtropical types are ill-equipped with life-history traits to persist through successive fires (Keith et al. unpubl. data). Conversely, rainforest ecosystems that occupy sheltered parts of landscapes conferring some protection from seasonal deficits may be more resilient than ecosystems in more exposed habitats.

The incidence of extreme drought is projected to increase in areas currently occupied by all forms of rainforest, but is likely to be most pronounced in areas supporting northern warm temperate rainforest (C2) cool temperate rainforest (C4), southern warm temperate rainforest (C0) and subtropical dry rainforest (C3) (Table 4). These changes are projected to be most strongly manifested in increases in the time spent under drought conditions (Table 4). In addition, projected upward movement of the cloud base to higher elevations will lead to increased exposure to drought and UVB radiation in ecosystems harnessing a high proportion of water from cloud cover such as northern warm temperate (C2) and cool temperate (C4) rainforests (Pennington et al. 2020, ESCC Hub).

Table 4. *Percent increase in the incidence of extreme drought as manifested by projected declines in standardised soil moisture index for the year 2070 relative to the 1995 baseline. Shading indicates values that are significant higher (orange) or lower (green) than the intercept (row 1: C0; $P<0.05$).*

Rainforest type	samples	Percent of time in drought (% increase over baseline)	Drought Duration (% increase over baseline)	Drought Frequency (% increase over baseline)	Drought Intensity (% increase over baseline)
Southern Warm Temperate RF (C0)	238	59	51	0	32
Lower North Floodplain Gallery RF (C1)	50	-28	-3	0	-15
Northern Warm Temperate RF (C2)	219	86	36	0	27
Subtropical Dry RF (C3)	154	55	25	-1	16
Cool Temperate Rainforest (C4)	146	66	47	0	31
Backhousia Dry RF (C5)	208	49	31	2	23
Western Vine Thickets (C6)	87	15	19	-11	0
Upland Subtropical RF (C7)	505	47	24	-3	15
Temperate/Subtropical RF (C8)	381	42	30	0	24
Tablelands and Coastal Rainshadow Dry RF (C9)	190	30	27	1	14
Sydney Sandstone Gallery RF (C10)	65	52	35	1	32
Southern Lowland RF (C11)	260	7	11	-5	5
Temperate Subtropical Dry RF (C12)	211	30	23	-4	13
Lowland Subtropical RF (C13)	347	48	33	-2	18

The strong association between drought and fire demonstrated by the 2019-2020 fires (Nolan et al. 2020) suggests that all rainforest ecosystems are likely to face increased exposure to the threat of fire, however there are currently few data available to determine which rainforest types are most at risk. There was significant variation among rainforest types in the proportion of samples burnt within the 2019-2020 fireground (Table 5). This variation may be due to differences in pre-fire drought conditions, fuel structure and flammability, the proximity to points of ignition and the context of surrounding vegetation. The relative contributions of these factors is unknown. Sampled locations for southern warm temperate (C0) and cool temperate (C4) rainforests were more likely to have burnt in the 2019-2020 fire than other rainforest types (Table 5, column 5). Both of these ecosystems had intermediate levels of exposure to extreme drought (Table 5, column 3), although the proportion of samples burnt was slightly lower where preceded by severe drought (C0 significant at $p<0.05$, C4 non-significant). A higher propensity to burn in these communities could therefore be attributable to fuel characteristics (e.g. more flammable elements or structure, higher volumes) or greater chance of ignition (proximity to flammable vegetation, exposure to fire fronts). Sample locations of Subtropical dry (C3), Sydney Sandstone Gallery (C10), Backhousia dry (C5), Temperate subtropical dry (C12) and Tableland and coastal rainshadow dry (C9) rainforests were all more likely to have burnt when preceded by severe drought conditions compared with sampled locations experiencing moderate drought conditions. Sampled locations of northern warm temperate rainforest (C2) had the lowest propensity to burn during the 2019-2020 fires (Table 5), irrespective of the degree of exposure to severe drought. This suggests that while this ecosystem may not suffer substantial increases in fire activity, even though it is projected to be among the most exposed rainforest type to future increases in drought duration (Table 4).

Post-fire regrowth of temperate subtropical dry rainforest one year after fire, with seedling recruitment of Dendrocnide excelsa*, one of the few tree species with a persistent soil seed bank. Yattah Yattah Nature Reserve, NSW. Image: D. Keith*

Beyond the declining water availability and increasing risk of drought and fire, there are potentially a wide range of more subtle effects associated with increases in atmospheric CO2 concentrations. For example, future declines in some foliavore populations have been postulated as a consequence of decreases in palatability and nutritional value of key food resources which are evident in samples grown under elevated CO2 concentrations (Kanowski 2001).

Table 5. *Incidence of antecedent drought (December 2018 – December 2019) and fire (2019-2020) among vegetation survey plots sampling different rainforest types. Shading indicates values significantly higher (orange) or lower (green) than the intercept (row 1: C0; $P<0.05$). Shading in column seven indicates significant fire-drought interactions (ie relative to column six).*

Rainforest type	samples	Drought affected (% of samples)	Samples within burn footprint (%)	% of samples within fire footprint	% of samples in mild drought that burnt	% of samples in severe drought that burnt
Southern Warm Temperate RF (C0)	238	47	171 (72%)	89	96	85
Lower North Floodplain Gallery RF (C1)	50	65	1 (2%)	NA	NA	NA
Northern Warm Temperate RF (C2)	219	35	100 (46%)	17	20	17
Subtropical Dry RF (C3)	154	18	69 (45%)	58	54	70
Cool Temperate Rainforest (C4)	146	51	83 (57%)	88	98	68
Backhousia Dry RF (C5)	208	58	88 (42%)	59	53	65
Western Vine Thickets (C6)	87	100	(0%)	NA	NA	NA
Upland Subtropical RF (C7)	505	24	88 (17%)	32	31	31
Temperate/Subtropical RF (C8)	381	80	87 (23%)	55	62	56
Tablelands and Coastal Rainshadow Dry RF (C9)	190	87	28 (15%)	61	25	67
Sydney Sandstone Gallery RF (C10)	65	56	25 (38%)	56	50	71
Southern Lowland RF (C11)	260	46	21 (8%)	52	64	17
Temperate Subtropical Dry RF (C12)	211	68	43 (20%)	37	31	53
Lowland Subtropical RF (C13)	347	25	20 (6%)	55	57	0

Table 6 provides a synopsis of the exposure of each listed rainforest community to the range of threats identified in Fig. 2. All communities have widespread exposure to high-severity impacts from multiple threatening processes, with contrasting threat syndromes characterising upland and lowland communities.

Table 6. *Threat diagnosis for major types of rainforest ecosystems in eastern Australia. Three components of threat ranked according to S - Severity (high/medium/low), E - Extent (universal/widespread/localised), T - Time frame (past/current/future). Multiple subscripts indicate threat components that span more than one level for respective ecosystem types. Red shading indicates threats ranked as high or high-medium severity, universal or widespread extent and current time frame for respective ecosystem types.*

EPBC listing	State listing	Climate change	Altered fire regimes	Disease	Erosion & sedimentation	Nutrient enrichment	Invasive plants	Invasive vertebrates	Livestock grazing	Land clearing	Vehicular & pedestrian access
Lowland Rainforest of Subtropical Australia		Sm, Eu, Tcf	Sm, Ew, Tcf	Sl, Ew, Tcf	Sm, El, Tpcf	Sm,El,Tc	Sh, Ew, Tc	Smh, Ew, Tc	Smh, Ew, Tc	Sh, Ew, Tpc	Sm, El, Tpcf
	Lowland rainforest NSW North Coast and Sydney Basin Bioregion (NSW)	Sm, Eu, Tcf	Sm, Ew, Tcf		Sm, El, Tpcf	Sm,El,Tc	Sh, Ew, Tc	Sl, Ew, Tc	Smh, Ew, Tc	Sh, Ew, Tpc	Sm, El, Tpcf
	Lowland rainforest on floodplain (NSW)	Smh, Eu, Tcf	Sm, Ew, Tcf		Sm, El, Tpcf	Sm,El,Tc	Sh, Ew, Tc	Smh, Ew, Tc	Smh, Ew, Tc	Sh, Ew, Tp	Sm, El, Tpcf
Illawarra-Shoalhaven Subtropical Rainforest		Sm, Eu, Tf	Sm, Ew, Tcf		Sl, El, Tpcf	Sm,El,Tc	Sh, Ew, Tc	Sm, Ew, Tc	Sl, El, Tc	Sh, Ew, Tpc	Sl, El, Tpcf
	Illawarra Subtropical Rainforest in the Sydney Basin Bioregion	Smh, Eu, Tf	Sm, Ew, Tcf		Sl, El, Tpcf	Sm,El,Tc	Sh, Ew, Tc	Sm, Ew, Tc	Smh, Ew, Tc	Sh, Ew, Tpc	Sl, El, Tpcf
	Milton Ulladulla subtropical Rainforest in the Sydney Basin Bioregion	Smh, Eu, Tf	Sh, Ew, Tcf		Sl, El, Tpcf	Sl,El,Tpc	Sh, Eu, Tpc	Sl, Ew, Tc	Sh, Ew, Tpc	Sh, Ew, Tpc	Sh, El, Tpcf
Not listed: Upland subtropical rainforest											
Littoral Rainforest and Coastal Vine Thickets of Eastern Australia		Sh, El, Tcf	Sm, El, Tcf	Sh, Elw, Tcf	Sh, El, Tpcf	Sl, El, Tpcf	Smh, Ewl, Tpf	Smh, Ew, Tcf	Sm, El, Tcf	Sh, El, Tcf	Sm, El, Tpcf
	Littoral Rainforest (NSW)	Sh, El, Tcf	Sh, El, Tcf	Sh, Elw, Tcf	Sh, El, Tpcf	Sl, El, Tpcf	Smh, Ewl, Tpf	Smh, Ew, Tcf	Sm, El, Tcf	Sh, El, Tcf	Sm, El, Tpcf

EPBC listing	State listing	Climate change	Altered fire regimes	Disease	Erosion & sedimentation	Nutrient enrichment	Invasive plants	Invasive vertebrates	Livestock grazing	Land clearing	Vehicular & pedestrian access
Western Sydney Dry Rainforest and Moist Woodland on Shale		Sm, Eu, Tf	Smh, Eu, Tpcf	Sl, El, Tcf	Sh, Ew, Tpcf	Sh, Ewl, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpc	Sl, El, Tp	Sh, Ew, Tpc	Smh, Ew, Tpcf
	Western Sydney Dry Rainforest (NSW)	Sm, Eu, Tf	Smh, Eu, Tpcf	Sl, El, Tcf	Sh, Ew, Tpcf	Sh, Ewl, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpc	Sl, El, Tp	Sh, Ew, Tpc	Smh, El, Tpcf
	Moist Shale Woodland in the Sydney Basin Bioregion	Sm, Eu, Tf	Smh, Eu, Tpcf	Smh, Ew, Tcf	Sh, Ew, Tpcf	Sh, Ewl, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpc	Smh, Ew, Tpcf	Sh, Ew, Tpc	Smh, El, Tpcf
not listed	Lowland Hunter Dry Rainforest	Sm, Eu, Tcf	Smh, Eu, Tpcf	Sl, El, Tc	Sh, Ew, Tpcf	Sl, Ewl, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpc	Smh, Ew, Tpcf	Sh, Ew, Tpc	Sm, El, Tpcf
not listed	Mount Kaputar high elevation Dry Rainforest land snail and slug community	Sh, Eu, Tcf	Sh, Ew, Tcf	Sl, El, Tc	Sl, El, Tpcf	Sl, El, Tpcf	Sl, Elw, Tpcf	Smh, Ew, Tpc	Sl, Elw, Tpc	Sl, El, Tpf	Sh, El, Tcf
not listed	Dry Rainforest of the South East Forests	Sm, Eu, Tcf	Smh, Eu, Tpcf	Sl, El, Tcf	Sh, El, Tpcf	Sl, Ewl, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpc	Smh, Ew, Tpcf	Sh, Ew, Tpc	Sm, El, Tpcf
not listed	Hunter Valley Vine Thicket	Sm, Eu, Tf	Smh, Eu, Tpcf	Sl, El, Tcf	Sl, El, Tpcf	Sl, El, Tpcf	Smh, Ew, Tpcf	Sm, Ew, Tpcf	Sh, Ew, Tpcf	Sh, El, Tcf	Sh, El, Tpcf
Semi-evergreen vine thickets of the Brigalow Belt		Sm, Eu, Tf	Sl, Eu, Tpcf	Sl, El, Tcf	Sh, El, Tpcf	Sl, El, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpcf	Sh, Ew, Tpcf	Sm, Ew, Tcf	Sl, El, Tpcf
	Semi-evergreen Vine Thicket in the Brigalow Belt South and Nandewar Bioregions	Smh, Eu, Tf	Smh, Ew, Tpcf	Sl, El, Tcf	Sl, El, Tpcf	Sl, El, Tp	Sh, Eu, Tpcf	Sh, Eu, Tpcf	Sh, Ew, Tpcf	Sh, Ew, Tpcf	Sh, El, Tpcf
not listed	Brogo Wet Vine Forest	Sh, Eu, Tcf	Sm, Eu, Tpcf		Sh, El, Tpcf	Sl, El, Tp	Sl, El, Tp	Sl, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, Elw, Tpc

For the first time, the working classification of rainforest ecosystems provides a systematic context for ecological communities that have been assessed and listed at national level, in relation to those that are yet to be assessed including some that appear eligible for future listing. Below, we examine the context of current listings for each of the four major groups of rainforest.

Tropical and subtropical lowland rainforests

Tropical and subtropical lowland rainforests of southeastern Australia include lowland, upland and subtropical/temperate variants. Lowland subtropical rainforests (C13) are comprehensively covered by the listings *Lowland Rainforest of Subtropical Australia and Littoral Rainforest and Coastal Vine Thickets of Eastern Australia under the EPBC Act 1999*. While there is compositional overlap between these two ecosystem listings, separate listings recognise important environmental, structural and functional differences which confer differential exposure and susceptibility to threats such as weed invasion, fire and climate change. In NSW, Lowland Rainforests (*sensu* EPBC listing) are represented in separate listings for floodplain and non-floodplain variants, in recognition of the functional importance of hydrological processes in the former, and the concomitant risks posed by changes in hydrological regimes as well as different trajectories of declines in historical distribution associated with the settlement of the floodplains. Lowland subtropical rainforests (C13) comprise the most diverse range of plant community types, collectively representing NSW 47 PCTs and 51 Queensland REs, of which 42 are listed as endangered or of concern under the Queensland *VM Act 1999*.

There are currently no listings covering upland subtropical rainforests (C13) (or components thereof) under either Commonwealth or state legislation. Among 11 PCTs and REs within this group, Keith et al. (2021) identified NSW PCT 3019 Northern Hinterland Baloghia-Booyong Subtropical Rainforest and Qld RE 12.8.5 Complex notophyll vine forest on Cainozoic igneous rocks as priorities for assessment due to the high proportion of their distribution impacted by the 2019-2020 fires. An assessment of impacts to these individual communities was beyond the scope of the current study, however, the 11 upland subtropical rainforests collectively were among the least impacted of rainforest ecosystems affected by the 2019-2020 fires, are relatively unaffected by weed invasion across their range and are exposed to less severe increases in future drought severity than other rainforest ecosystems. Future listings of upland subtropical rainforests are therefore more appropriately targeted at the level of individual plant community types.

Temperate subtropical rainforests are currently represented in two TEC listings in NSW (Illawarra Subtropical Rainforest in the Sydney Basin Bioregion and Milton Ulladulla subtropical Rainforest in the Sydney Basin Bioregion) which collectively comprise Illawarra-Shoalhaven Subtropical Rainforest of the Sydney Basin Bioregion as listed under the *EPBC Act 1999*. Four out of eight NSW temperate subtropical rainforest PCT types are covered by these listings (Table 2). Of the four PCTs not included under any current listing, NSW PCT 3097 Northern Escarpment Dry Rainforest was recommended for priority assessment by Keith et al. (2020) following the 2019-2020 fires. Temperate subtropical rainforests are almost universally dominated by species observed to have been heavily impacted by the 2019-2020 fires and, in addition, examples burnt on the south coast have been extensive impacted by weed invasion following the fires. Future assessments for listing of temperate subtropical rainforests should consider a broad listing encompassing all variants.

Dry rainforests and vine thickets

Dry rainforests and vine thickets of southeastern Australia comprise five broad classes in our syn-taxonomic treatment including two tropical and temperate-subtropical variants (C3, C12), western vine thickets (C6), Backhousia dry rainforests (C5) and dry rainforests of Tablelands and Coastal Rainshadow Valleys (C9). Subtropical dry rainforests (C3) include five NSW PCTs and 12 Queensland EVCs of which 10 are listed as endangered or Of Concern under the Vegetation Management Act. There is overlap between the temperate-subtropical dry rainforest class (C12) and the temperate-subtropical rainforests (C8) occurring on the south coast described in the previous section, and further work is required to clarify the status of these communities (Table 1). Both ecosystems (C3 and C12) are susceptible to invasion by *Lantana camara* (Table 3), have a relatively high propensity to burn (Table 5), are at significant risk of exposure to increases in drought severity (although less so for C12; Table 4) and were significantly more likely to have burnt when under conditions of extreme drought in the 2019-2020 than otherwise (Table 5). Given the well-documented interactive effects between fire and growth of Lantana populations (Duggin and Gentle 1998, Berry et al. 2011) both classes of rainforest warrant assessment for conservation risk.

Multiple state listings cover variants of tablelands and coastal rainshadow dry rainforest, however only one of these is included under a Commonwealth listing (Table 2). Variants of this ecosystem are exposed to a diverse range of threats (Table 6), however in most cases these arise from a common exposure to landscape fragmentation, agricultural production and associated impacts of exotic herbivores. While this ecosystem was not strongly represented within the 2019-2020 fireground, there is evidence samples had a reasonably high propensity to burn and were significantly more likely to do so under conditions of extreme drought (Tables 4 & 5). Tablelands and coastal rainshadow dry rainforests are at risk of exposure to droughts of increased severity and an assessment for a broad listing incorporation all regional variants is warranted.

The Commonwealth-listed Semi-evergreen vine thickets of the Brigalow Belt (North and South) and Nandewar Bioregions incorporates the NSW state-listed Semi-evergreen Vine Thicket in the Brigalow Belt South and Nandewar Bioregions (described by two PCTs) and ten Queensland REs of which seven are listed as endangered or Of Concern under the Vegetation Management Act. We did not identify any other state units covered by this class. There are no current TECs covering *Backhousia* dry rainforest (C5) or parts thereof. This ecosystem incorporates nine PCTs of which two were recommended by Keith et al. (2020) for priority assessment following the 2019-2020 fires (NSW PCT 3098 Northern Escarpment Grey Myrtle Gully Rainforest, NSW PCT 3106 South Coast Grey Myrtle Dry Rainforest). The ecosystem is moderately susceptible to invasion by *Lantana camara* (Table 3), has a relatively high propensity to burn (Table 5), is at significant risk of exposure to increases in drought severity (Table 4) and was significantly more likely to have burnt when under conditions of extreme drought in the 2019-2020 than otherwise (Table 5). An assessment for a broad listing incorporation all regional variants should be considered.

Warm temperate rainforests

We identified five classes of warm temperate rainforest of which only the Victorian elements of our southern variant (C0) are covered by state listings. Southern warm temperate rainforest (C0) had the highest propensity to burn of all our classes and warrants assessment for a broad listing given it is also exposed to increased risk of extreme drought in the future. Such an assessment could consider the inclusion of Sydney sandstone gallery rainforest (C10) which had a relatively low exposure within the 2019-2020 fire footprint but demonstrated a very high propensity to burn in areas exposed to severe drought (Table 5).Northern warm temperate rainforest (C2) demonstrated the lowest propensity to burn of all rainforest classes despite a high degree of exposure within the 2019-2020 fireground, irrespective of pre-fire drought conditions. This ecosystem is also currently relatively unaffected by weed invasions, however it occupies areas with the worst projections for future extreme drought scenarios (Table 4) as well as continued rises in cloud base elevation. There is evidence that upward migration of lowland species is occurring and significant contractions in the range of this ecosystem are possible.

Cool temperate rainforests

Cool temperate rainforests demonstrated a very high propensity to burn during the 2019-2020 fires. None of Australia's cool temperate rainforests is currently listed at Commonwealth or state legislation. This group of ecosystems is at high risk of decline due to climate change and future fires, and consideration of a broad listing incorporating all regional variants is warranted.

Fire-killed trunk of Acacia maidenii *with abundant post-fire recruitment of invasive* Solanum mauritianum *overtopping the native* Solanum aviculare. *Fire events provide 'windows' of opportunity for invasion of weed species. Temperate subtropical dry rainforest at Yattah Yattah Nature Reserve NSW. Image: D. Keith.*

Peatlands

The three major groups of peat-accumulating ecosystems are characterised by contrasting syndromes of threats (Table 9). Heath swamps have the most heterogeneous threat syndromes. They are primarily threatened by climate change, although particular units are threatened by altered fire regimes; hydrological change related to underground mining; nutrient enrichment and erosion and sedimentation related to land use within their catchments. Montane peatlands are primarily threatened by a suite of threats associated with rural land use and infrastructure development (roads, water pipelines, power easements). These threats include land clearing, livestock grazing, invasive vertebrates (notably pigs), nutrient enrichment, erosion and sedimentation and vehicular access. They are also threatened by climate change and altered fire regimes. Alpine bogs and fens are universally threatened by climate change and altered fire regimes, as well as invasive vertebrates (notably horses and pigs). Parts of their distribution are also threatened by livestock grazing, erosion and sedimentation.

As for rainforests, all nine peatland types assessed are threatened by a drying climate in southeastern Australia. Shifts in moisture avaiulability were most evident through increased percentage of time spent in severe drought, which is projected to more than double for New England and Newnes plateau swamps, and increase by 50-100% for all others (Table 7). The intensity of droughts experienced by peatland ecosystems was projected to increase by 30-60% for Blue Mountains, Coastal upland, New England, Newnes plateau swamps and Montane bogs and fens, and by 17-25% for other peatland types (Table 7). The frequency of droughts is projected to undergo negligible change, except for Alpine bogs and fens and Coastal upland swamps (22-24% increase).

Table 7. *Percent increase in the incidence of extreme drought as manifested by projected declines in standardised soil moisture index for the year 2070 relative to the 1995 baseline.*

Peatland type	# swamps mapped	Percent of time in drought (% increase over baseline)	Drought Duration (% increase over baseline)	Drought Frequency (% increase over baseline)	Drought Intensity (% increase over baseline)
Alpine bogs and fens	9446	84.8	42.7	24.3	17
Blue mountains swamps	1684	93.3	43.9	0	58.4
Coastal upland swamps	1359	83.1	33.4	22.5	39.1
Montane peatlands and swamps	4116	74.2	44.3	-0.2	32.5
New England heath swamps	378	142.9	64.6	0	58.7
Newnes plateau shrub swamps	170	110.5	48.3	0	56.8
Penrose-Morton shrub swamps	325	50.6	36.6	0	25.6
Sandplain swale swamps	1970	67.8	29.1	4.1	20.3

In the lead up to the 2019-20 fires, peatland ecosystems were experiencing severe drought, with rainfall in the six month from July to December 2019 in the lowest 4% of all historic records for all types except Alpine bogs and fens, which were within lowest 12% of historic rainfall records (Table 8). Five peatland types experienced rainfall levels for that period in the lowest 2% of all historic records. The severe drought was prolonged, with rainfall in the 2.5 years prior to December 2019 in the lowest 6% of all historic records for all types except Coastal Upland Swamps, which were within lowest 11% of historic rainfall records (Table 8). For that extended period, five peatland types experienced rainfall levels in the lowest 2% of all historic records.

Table 8. Incidence of antecedent drought (December 2018 – December 2019) and fire (2019-2020) among mapped polygons of different peatland types. Mean fire severity was estimated from Gibson et al. (2020) based on their 1 (low) – 5 (high) severity scale.

Peatland type	# swamps mapped	Rainfall Jul2019-Dec2019 (mean percentile relative to historic records)	Rainfall Jul2017-Dec2019 (mean percentile relative to historic records)	% swamps burnt	Mean severity when burnt
Alpine bogs and fens	9446	6.5	11.7	16.6	4.2
Blue mountains swamps	1684	6.4	3.8	56.2	3.7
Coastal upland swamps	1359	10.9	1.4	0.4	3.3
Montane peatlands and swamps	4116	1.2	1.4	24.5	3.3
New England heath swamps	378	0.9	0.9	75.1	3.6
Newnes plateau shrub swamps	170	1.4	3.3	99.4	4.1
Penrose-Morton shrub swamps	325	2.7	0.99	15.7	4.1
Sandplain swale swamps	1970	1.9	4.6	51	4

Coastal upland swamps were the only peatland type that essentially avoided fire during the 2019-2020 season. In contrast, all but one of the 170 mapped Newnes plateau swamps burnt, as did more than three-quarters of mapped New England swamps and more than half of mapped Blue Mountains swamps and Sandplain swale swamps, while 15-25% of other peatland types were burnt (Table 8). When burnt, peatlands consistently experienced severe fires (Table 8).

Table 9 provides a synopsis of the exposure of each listed peatland type to the range of threats identified in Fig. 3. All peatland types have widespread exposure to high-severity impacts from at least two threatening processes, except Sandplain swale swamps (widespread exposure to one high-severity threat), with contrasting threat syndromes characterising heath swamp, montane and alpine communities. Although climate-related threats to Sandplain swale swamps are currently ranked at 'medium' severity due to projections of less severe decline in soil moisture, this could increase as climate trajectories unfold.

Collapse of a Newnes plateau shrub swamp peatland ecosystem caused by the combined effect of hydrological disruption and fire. Priori underground longwall mining drained the perched aquifer that sustained this former peatland, reducing its resilience to fire and predisposing the system to collapse after fire. Carne West swamp shown here 12 months after fire which consumed peat, killing plant regenerative organs and seed banks, resulting in loss of species and regrowth biomass 100 less than comparable unmined reference swamps. Post-fire incursion of eucalypt seedlings into the drier soils is transforming parts of the former peatlands into a species-poor eucalypt thicket. Newnes State Forest, NSW. Image: D. Keith

Table 9. Threat diagnosis for major types of peat-accumulating ecosystems in eastern Australia. Three components of threat ranked according to S - Severity (high/medium/low), E - Extent (universal/widespread/localised), T - Time frame (past/current/future). Multiple subscripts indicate threat components that span more than one level for respective ecosystem types. Red shading indicates threats ranked as high or high-medium severity, universal or widespread extent and current time frame for respective ecosystem types.

EPBC listing	State listing	Climate change	Longwall mining	Altered fire regimes	Erosion & sedimentation	Nutrient enrichment	Invasive plants	Invasive vertebrates	Livestock grazing	Land clearing	Vehicular & pedestrian access
Coastal Upland Swamp		Sh, Eu, Tcf	Sh, Ew, Tcf	Sm, Eu, Tpcf	Sm, El, Tpcf	Sl,El,Tc	Sl, El, Tp	Sl, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, El, Tpcf
	Coastal Upland Swamp (NSW	Sh, Eu, Tcf	Sh, Ew, Tcf	Sm, Eu, Tpcf	Sm, El, Tpcf	Sl, El, Tc	Sl, El, Tp	Sl, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, El, Tpcf
Temperate highland peat swamps on sandstone (sandstone component)		Sh, Eu, Tcf	Sh, Ewl, Tcf	Sm, Eu, Tpcf	Smh, Ewl, Tpcf	Smh, Ewl, Tpcf	Slm, Ewl, Tpf	Slm, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, El, Tpcf
	Blue Mountains swamps (NSW)	Sh, Eu, Tcf	Sh, El, Tcf	Sm, Eu, Tpcf	Sm, El, Tpcf	Smh, Ewl, Tpcf	Sm, El, Tpf	Slm, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, El, Tpcf
	NSW & ACT (JB) not listed: Shoalhaven-Penrose sandstone swamps	Sh, Eu, Tcf	Sh, El, Tcf	Sm, Eu, Tpcf	Sh, Ew, Tpcf	Sm, Ewl, Tpcf	Slm, El, Tpf	Slm, Ew, Tc	Sl, El, Tp	Sh, Ew, Tp	Sm, Elm, Tpcf
	Newnes Plateau Shrub Swamp (NSW	Sh, Eu, Tcf	Sh, Ew, Tcf	Sm, Eu, Tpcf	Sh, Ew, Tpcf	Sl, El, Tpcf	Sl, El, Tpf	Sl, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, Elm, Tpcf
Alpine Sphagnum bogs and associated fens		Sh, Eu, Tcf	-	Smh, Eu, Tpcf	Sh, Ew, Tpcf	Slm, El, Tp	Sm, Elw, Tpcf	Smh, Ewl, Tpcf	Sh, Elw, Tpc	Sh, El, Tp	Sm, El, Tpcf
	Alpine Bog Community (Vic)	Sh, Eu, Tcf	-	Smh, Eu, Tpcf	Sh, Ew, Tpcf	Slm, El, Tp	Sm, Elw, Tpcf	Smh, Ewl, Tpcf	Sh, Elw, Tpc	Sh, El, Tp	Sm, El, Tpcf
	Fen (Bog Pool) Community (Vic)	Sh, Eu, Tcf	-	Sl, El, Tpcf	Sh, Ew, Tpcf	Sl, El, Tp	Sm, Elw, Tpcf	Smh, Ewl, Tpcf	Sh, El, Tpc	Sh, El, Tp	Sm, El, Tp
	Alpine Sphagnum bogs and fens (ACT)	Sh, Eu, Tcf	-	Smh, Eu, Tpcf	Sh, Ew, Tpcf	Slm, El, Tp	Sm, Elw, Tpcf	Smh, Ewl, Tpcf	Sh, El, Tp	Sh, El, Tp	Sm, El, Tp

EPBC listing	State listing	Climate change	Longwall mining	Altered fire regimes	Erosion & sedimentation	Nutrient enrichment	Invasive plants	Invasive vertebrates	Livestock grazing	Land clearing	Vehicular & pedestrian access
	NSW not listed: Alpine bogs and fens	Sh, Eu, Tcf	-	Smh, Eu, Tpcf	Sh, Ew, Tpcf	Slm, El, Tp	Sm, Elw, Tpcf	Sh, Ew, Tpcf	Sh, El, Tpc	Sh, El, Tp	Sm, El, Tp
Assemblages not currently listed under EPBC Act											
	NSW & Qld not listed: Sandplain swale bogs	Sm, Eu, Tcf	-	Smh, Eu, Tpcf	Sl, El, Tpcf	Sl, El, Tp	Sl, El, Tpc	Sl, Ew, Tc	Sl, El, Tp	Sh, Elw, Tp	Sm, El, Tp
	NSW not listed: Clarence sandstone swamps	Sh, Eu, Tcf	-	Sm, Eu, Tpcf	Sh, El, Tpcf	Sl, El, Tp	Sl, El, Tp	Sl, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, Elw, Tpc
	NSW not listed: New England granite bogs	Sh, Eu, Tcf	-	Sm, Eu, Tpcf	Sh, El, Tpcf	Sl, El, Tp	Sl, El, Tp	Slm, Ew, Tc	Sl, El, Tp	Sh, El, Tp	Sm, El, Tp
	NSW not listed: Southeast corner lowland bogs	Sh, Eu, Tcf	-	Sm, Eu, Tpcf	Sh, Ew, Tpcf	Slm, El, Tp	Slm, Elw, Tpc	Sm, Ew, Tc	Slm, El, Tpc	Sh, El, Tp	Sm, Elw, Tpc
	Montane Swamp Complex Community (Vic)	Sh, Eu, Tcf	-	Smh, Eu, Tpcf	Sh, El, Tpcf	Sh, Ew, Tpcf	Sh, Ew, Tpcf	Smh, Ew, Tpcf	Sh, Ew, Tpcf	Sh, Ew, Tpc	Smh, Ew, Tpcf
	*Montane Peatlands and swamps (NSW)	Sh, Eu, Tcf	-	Smh, Eu, Tpcf	Sh, El, Tpcf	Sh, Ew, Tpcf	Sh, Ew, Tpcf	Smh, Ew, Tpcf	Sh, Ew, Tpcf	Sh, Ew, Tpc	Smh, Ew, Tpcf
	Carex Sedgeland (NSW)	Sh, Eu, Tcf	-	Sl, Eu, Tpcf	Sh, El, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpcf	Smh, Ew, Tpcf	Sh, Ew, Tpcf	Sh, Ew, Tpc	Smh, Ew, Tpcf

* NSW listing partly included within EPBC listing of Temperate highland peat swamps on sandstone

Management strategies (Aim 3)

Management strategies are needed to promote the maintenance of ecological diversity and functions of rainforest and peatland ecosystems by providing guidance for:

- planning, management and restoration activities for the ecosystems by landholders, Natural Resource Management authorities and community groups;
- regulatory decisions relevant to development applications, including conditions for approval for relevant under relevant legislation; and
- prioritising investments from public and private funding programs.

The strategies bring together a suite of measures for protection, research and monitoring, management, restoration, communication and engagement to reduce risks of decline and degradation by abating threatening processes diagnosed in Tables 6 and 9. The strategies focus primarily on risk reduction for major threat syndromes to which different groups of ecosystems are exposed and susceptible, as well as cross-cutting strategies that support effective governance and implementation.

In addition to ecosystem-specific risk reduction strategies listed below, all rainforest and peatland ecosystems would benefit substantially from climate mitigation action, which would reduce the severity and extent of ecosystem degradation and the rates of decline.

Rainforests

Strategy 1. Implement regulatory mechanisms to prevent further clearing of rainforest ecosystems

Some rainforest ecosystems occur in rural landscapes and on private lands or grazing leases where they are exposed to ongoing threat of clearing. Mitigating the threat of clearing depends on i) accurate assessment of the conservation risks faced by different rainforest ecosystems; ii) comprehensive representation of threatened ecosystems in regulatory frameworks; iii) correct diagnosis of the rainforest types in the field; iv) appropriate planning and regulatory policies and v) adequate monitoring and law enforcement programs. Rainforest ecosystems particularly threatened by clearing include lowland subtropical rainforests, subtropical dry rainforests, lowland temperate rainforests, littoral rainforests, semi-evergreen vine thickets and tableland and coastal rainshadow dry rainforests. The following actions are priorities for these ecosystems:

1.1 Review the classification of rainforest ecosystems in Australia and develop a unifying classification framework with sufficient thematic detail to represent broad rainforest assemblages with similar functional attributes, dependencies and threat syndromes, including explicit cross-walks to state and regional level classification units.

1.2 Undertake IUCN assessments of conservation risk for all rainforest ecosystems exposed to significant threats and ensure that threatened ecosystems are listed on state and Commonwealth schedules with appropriate risk categorisations.

1.3 Support the development of descriptive texts, distribution maps and identification tools to facilitate correct identification of rainforest ecosystems in the field.

1.4 Strengthen planning and regulatory policies to protect rainforest.

1.5 Engage local communities and implement law enforcement programs to promote awareness of obligations and penalties in relation to the conservation of remnant rainforest ecosystems.

Strategy 2. Manage risk of fire to rainforest ecosystems

Fire management can reduce risks of fire in rainforest ecosystems as well as damage by fire suppression and hazard reduction operations. All rainforest ecosystems are sensitive to fire-related threats however some types may require a greater focus than others because they are either inherently more flammable, they occur locations which are more likely to be exposed to fire due to proximity to highly flammable vegetation or landforms which promote high severity fires or they faced increased risks associated with future drought. Rainforest ecosystems disproportionately affected by the 2019-2020 fire event were southern warm temperate rainforests and cool temperate rainforests (approximately 90% of samples burnt). A smaller proportion of samples of northern warm temperate rainforest were burnt than other rainforest types (< 20% of samples). The following actions are priorities:

2.1 Avoid or prevent fire ignitions for the duration of forecasts of extreme fire weather, e.g. through total fire bans, closure of management areas, and regular surveillance of, and rapid response to, evidence of ignitions.

2.2 Avoid or prevent fire ignitions during prolonged periods of low fuel moisture or low soil moisture (Nolan et al. 2020).

2.3 Develop and implement measures to restrict vehicular access, use of equipment and construction of fire control lines through sensitive rainforest vegetation and soils during fire suppression and hazard reduction operations.

Strategy 3. Exclude livestock access

Rainforest ecosystems occurring in rural landscapes and on private lands or grazing leases are exposed to domestic livestock. Cattle and horses, as well as pigs, sheep and goats, cause sustained damage to vegetation and soils, with associated changes to drainage, primarily by trampling and secondarily though herbivory (Table 7), although grazing of cattle in rangelands may not be incompatible with the conservation of subtropical dry rainforest under some circumstances (Fensham 1996). The following actions are priorities for rainforest ecosystems that are currently most exposed to severe threats associated with domestic livestock grazing, including lowland subtropical rainforests, tableland and coastal rainshadow dry rainforests and semi-evergreen vine thickets.

3.1 Exclude domestic livestock from rainforest remnants with appropriate fencing between production pastures with a buffer zone of at least 20 m.

3.2 Undertake appropriate stabilisation works and weed control to restore rainforest ecosystems degraded by past livestock activity.

Strategy 4. Exclude polluted water inflows

Rainforest ecosystems occurring in heavily fragmented landscapes associated are subject to nutrient influxes carried by urban or agriculture effluent. High nutrient loads have a range of impacts including inhibiting the activity of detritovores (Garcia et al. 2017), increasing the competitive advantages of exotic species over natives (Gentle and Duggin 1998, Lake and Leishman 2004) and decreasing species evenness and diversity by favouring species with the capacity to increase nutrient uptake (Siddique et al. (2010). Rainforest types occurring on coastal lowlands, coastal rainshadow valleys and other areas with high levels of urban development or agricultural production are most susceptible to this threat. Priority actions are:

4.1 Regulate effluent flows using appropriate structures and technologies to trap sediments and divert nutrient fluxes.

4.2 Encourage sustainable agriculture practices which reduce nutrient fluxes by using more efficient application methods which deliver doses better calibrated to crop uptake capacity and concentrated in uptake zones.

4.3 Prioritise infrastructure upgrades in urban areas presently reliant on septic disposal systems or where separation of stormwater and sewerage systems is inadequate.

Strategy 5. Control invasive exotic plants

Rainforest ecosystems subjected to high levels of clearing and fragmentation also experience significant competition from invasive exotic plant species. Exotic species compete with native species for light, moisture and nutrient leading to decreased native plant diversity , altered vegetation structure and diminution of habitat and resources for fauna species. Invasion is frequently associated with disturbance (via fire, logging, grazing of domestic stock) or natural tree death. One of the most widespread exotic species is Lantana camara (NSW TSSC 2006a), a species which rapidly establishes following disturbance (Duggin and Gentle 1998) and may promote conditions for its own spread by altering the structure of the fuel layer, leading to a higher incidence of fire, particularly in subtropical dry rainforests (Berry et al. 2011). Other species of concern include a wide range of exotic vines and scramblers (NSW TSSC 2006b). Rainforest ecosystems threatened by invasion of exotic plant species are lowland subtropical rainforests, subtropical dry rainforests, temperate/subtropical dry rainforest and temperate lowland rainforests. Priority actions are:

5.1 Reduce disturbance to rainforest remnants by implementing strategies 2 (reduce incidence of fire), 3 (exclude domestic stock) and 7 (control access by vehicles and pedestrians).

5.2 Build capacity to undertake regular surveillance for weed invasions and rapid response to control outbreaks including a specific focus on rainforest ecosystems affected by fire.

5.3 Undertake rainforest rehabilitation including the planting of buffer strips along remnant boundaries to reduce weed propagule influxes and conditions conducive to exotic species establishment along remnant margins (Sonter et al. 2010).

Strategy 6. Control invasive animals

Control of invasive herbivores limits declines in plant species with survival, growth and/or reproduction adversely impacted by herbivory. Control of exotic predators such as cats, foxes and dogs reduces mortality in fauna species. Priority actions are:

6.1 Construct fences to protect rainforest remnants of high conservation value from at local scales.

6.2 Develop integrated, cross-tenure programs to control invasive species at landscape scales

Strategy 7. Protect susceptible elements of rainforests against impacts of Myrtle Rust disease

Myrtle rust is currently causing precipitous declines in distinctive trees of rainforest ecosystems and their associated biota. Impacts are likely to be exacerbated by fire because it exposes more susceptible young foliage to infection during the regrowth phase. The most vulnerable rainforests are subtropical types, as these have greatest diversity of susceptible species and the disease is (so far) most active in warm climates. Priority actions are:

7.1 Identify priority sites for monitoring based on healthy populations of rare or structurally dominant Myrtaceae species.

7.2 Undertake surveillance to identify outbreaks of myrtle rust in priority sites.

7.3 Treat susceptible trees to increase disease resistance where feasible.

7.4 Collect germplasm to develop ex situ repositories of rainforest elements threatened by the disease.

Strategy 8. Restore degraded rainforests

Many degraded rainforests have some propensity for recovery through natural (unassisted) regenerative processes (Shoo et al. 2016), however, alternative ecosystem trajectories may result from invasions of exotic species and legacies of changes in soil structure and chemistry, even though degradation may have slowed or ceased. Active management or assisted natural regeneration may help to promote restoration pathways to functional native rainforest ecosystems, especially in the most extensively degraded lowland rainforest types. Priority actions are:

8.1 Remove or neutralise the causes of degradation, such as ongoing exogenous disturbances to canopies, understories, fauna or soils.

8.2 Undertake judicious interventions, such as selective plantings, weed control, translocations,

8.3 Prepare and implement contingency plans to promote recovery or exploit restoration opportunities (e.g. for weed control) for restoration after major disturbance events such as fires, landslides, floods or storm damage.

8.4 Monitor rainforest responses to restoration actions relative to appropriate local reference sites, and adapt management actions based on the evidence to improve restoration outcomes.

8.5 Engage traditional owners and local communities in the design, implementation and outcomes of restoration projects (see Strategy 11).

Cross-cutting Strategy 9. Undertake research and monitoring

Effect mitigation of threats to rainforest ecosystems is currently limited by information gaps in how different types of rainforests are affected by known and emerging threats, and in the efficacy of alternative mitigation strategies. For example, the evidence from the 2019-20 fires suggests there may be differences among broad ecosystem types in terms of both propensity to burn and susceptibility of constituent species to decline, however it is not known what combination fuel properties, the degree of exposure to ignition and local (and antecedent) conditions at the time of the fire are implicated. There are few quantitative data available to assess the response to fire of individual species and subsequent trajectories of recovery or decline. Furthermore, there is a need to develop effective restoration techniques tailored to specific species assemblages and threat contexts.

10.1 Undertake research to improve understanding of how fire regimes, feedbacks and dependencies mediate resistance and resilience of function and diversity in different rainforest ecosystems.

10.2 Undertake research to project responses of rainforest function and diversity ecosystems to alternative climate scenarios.

10.3 Undertake research to improve methods of surveillance and monitoring of Myrtle rust disease in rainforest ecosystems and to develop more effective methods for disease control.

10.4 Undertake research to improve understanding and management capacity to maintain rainforest function and diversity in fragmented landscapes, for example, the role of key animals as mobile links.

10.5 Undertake research to improve performance of techniques for restoration of rainforest vegetation, fauna, soils and function.

Cross-cutting Strategy 10. Communicate and educate about the values and roles of peatland ecosystems

The uniqueness, values and sensitivity of Australian rainforests are relatively well appreciated across the community, industry and government sectors. The following strategies will help build momentum and support from this base for more proactive mobilisation and engagement in rainforest conservation action.

10.1 Develop and implement a communications plan to meet the information requirements of a range of partners and stakeholders and raise awareness in the general public.

10.2 Develop education and extension materials for targeted audiences within communities, land managers and businesses with a stake in the sustainability of peatland ecosystems.

10.3 Regularly disseminate outputs of peatland research, monitoring and management through research literatures, meetings, social and traditional media.

Cross-cutting Strategy 11. Engage community in conservation action

Conservation action is most effective when local communities are engaged in their development, implementation and outcomes, as demonstrated in numerous past and present rainforest conservation activities. As well as biodiversity conservation, rainforests make important cultural and spiritual contributions to human well-being. Community engagement also helps to attract resources and other support to undertake essential work. The following strategies will help realise these benefits for Australian rainforests.

11.1 Provide opportunities for local Indigenous community engagement in implementation of biodiversity conservation, while supporting connection to country.

11.2 Develop and maintain relationships with key partners in the community and business sectors, and key land managers.

11.3 Engage local community groups in development and implementation of strategies 1-10.

11.4 Promote interaction and sharing of knowledge and resources across a network of community groups working in different rainforest ecosystems.

11.5 Work with partners and stakeholders to identify and secure funding to support implementation of actions.

Peatlands

Strategy 1. Increase representation in Protected Areas

Representation of peatlands in Protected Areas (PAs) within the National Reserve System directly limits loss of habitat by preventing land use change, vegetation clearing and/or earthworks and drainage works (Fig. 2). While levels of statutory protection vary across different categories of PA within the National Reserve System, some categories of PA prohibit underground mining, and thus also offer protection against disruption of hydrological processes by underground mining (Fig. 2). PAs also indirectly abate the impacts of climate change by reducing other pressures that exacerbate or accelerate adjustments to a drier climatic regime that is eroding the excess of precipitation over evapotranspiration essential to peatland development and persistence (Fig. 2).

1.1 To ensure effectiveness of threat abatement within PAs, management plans for existing PAs should exclude infrastructure and service corridors, including walking tracks, from buffer areas around all peatland ecosystems.

1.2 Priorities for expansion of the National Reserve System should be directed to peatland types that are most severely threatened by land use change and underground longwall mining, and least represented within existing PAs. These include three peatland systems threatened severely, extensively and currently by land use change (Table 4): Montane Swamp Complex Community (Vic); Montane Peatlands and swamps (NSW); and Carex Sedgeland (NSW); and two threatened by longwall mining (Table 4): Newnes Plateau Shrub Swamp (EPBC, NSW) and Coastal Upland Swamps (EPBC, NSW).

1.3 Strengthen planning and regulatory policies to protect peatlands.

1.4 Implement community engagement and law enforcement programs to promote awareness of obligations and penalties in relation to the conservation of peatland ecosystems.

Strategy 2. Implement regulatory mechanisms to exclude incompatible development in catchments and underground

Regulatory mechanisms enabled by environmental legislation and policy can directly avoid or mitigate habitat loss caused by certain types of land use change, infrastructure development and longwall mining (Fig. 2). Indirectly, they can also be used to avoid or mitigate threats such as erosion, sedimentation, nutrient enrichment and weed invasion by regulating development in peatland catchments (Fig. 2).

The following actions are priorities for conservation of peatland ecosystem types that are threatened severely, extensively and currently by regulated actions, including land clearing, development of infrastructure and longwall coal mines. These include: Montane Swamp Complex Community (Vic); Montane Peatlands and swamps (NSW); and Carex Sedgeland (NSW); Newnes Plateau Shrub Swamp (EPBC, NSW); and Coastal Upland Swamps (EPBC, NSW) (Table 4); as well as other peatland types where severe threats are localised, such as Alpine bogs and fens (EPBC, Vic, ACT); and Blue Mountains Swamps (EPBC, NSW) (table 4).

2.1 Use regulatory approval processes to implement the mitigation hierarchy, to avoid impacts of proposed development by locating surface structures outside peatland catchments and by excluding peatlands from longwall mining footprints with appropriate buffer zones to avoid warping, cracking and subsidence impacts on the peatland system (Mason et al. 2021).

2.2 Where some projected impacts cannot be avoided, apply the mitigation hierarchy to minimise any residual impacts by requiring alternative development designs and mitigation measures.

2.3 Where some projected impacts cannot be avoided, require appropriate restoration actions to be implemented at the earliest time after impacts occur.

2.4 Implement measures such as bonds and compliance penalties to reduce risks of unforeseen impacts or breaches of development conditions and post-project restoration commitments

Strategy 3. Manage fire regimes

Fire management can reduce risks of severe peat fires and high frequency fires, as well as damage by fire suppression and hazard reduction operations. As all peatlands systems are sensitive to these fire-related threats, the following actions are priorities for all types listed in Table 4, except where noted.

3.1 Avoid or prevent fire ignitions for the duration of forecasts of extreme fire weather, e.g. through total fire bans, closure of management areas, and regular surveillance of, and rapid response to, evidence of ignitions.

3.2 Avoid or prevent fire ignitions during prolonged periods of low fuel moisture or low soil moisture (Nolan et al. 2020).

3.3 Avoid successive fires separated by intervals less than the critical minimum duration to ensure maintenance of structure and diversity. This minimum interval will vary between peatland ecosystems (longest for Alpine Sphagnum bogs, shortest for Carex fens), but generally is greater than 10 years.

3.4 Develop and implement measures to restrict vehicular access, use of equipment and construction of fire control lines through sensitive peatland vegetation and soils during fire suppression and hazard reduction operations.

3.5 For Coastal Upland Swamps (EPBC, NSW), where appropriate, burn strategically or exclude fires to limit competitive exclusion of peatland biota by dominance of high densities of tall shrubs (Keith et al. 2007; Mason et al. 2017). At present, this action is not required for other peatland communities, which are not known to be affected by high densities of tall shrubs.

Strategy 4. Exclude livestock access

Some peatland types occur in rural landscapes and on private lands or grazing leases where they are exposed to domestic livestock. Cattle and horses, as well as pigs, sheep and goats, cause sustained damage to vegetation and soils, with associated changes to drainage, primarily by trampling and secondarily though herbivory (Table 4). The following actions are priorities for peatland types that are currently most exposed to severe threats associated with domestic livestock grazing, including Alpine bogs and fens (EPBC, Vic, ACT), Montane Swamp Complex Community (Vic), Montane peatlands and swamps (NSW) and Carex Sedgeland (NSW).

4.1 Exclude domestic livestock from peatlands with appropriate fencing between production pastures and peatlands with a buffer zone of at least 20 m.

4.2 Ensure that livestock are excluded during sensitive post-fire regeneration stages of vegetation recovery.

4.3 Undertake appropriate stabilisation works and weed control to restore peatland ecosystems degraded by past livestock activity (see Strategies 6 and 9).

Strategy 5. Exclude polluted water inflows

Some peatland types are exposed to nutrient enrichment, erosion and sedimentation where urban, industrial, forestry or agricultural land uses operate within their catchments. The following actions are priorities, particularly for Alpine bogs and fens (EPBC, Vic, ACT), Montane Swamp Complex Community (Vic), Montane peatlands and swamps (NSW), Carex Sedgeland (NSW), Blue Mountains swamps (NSW) and Newnes Plateau shrub swamps (NSW).

5.1 Limit expansion or intensification of infrastructure, urban development, forestry and agricultural land uses in the catchments.

5.2 Control and limit application of fertilisers.

5.3 Redirect effluent and stormwater and install and maintain sediment traps and nutrient sequestration facilities to avoid influx of polluted water into peatlands.

5.4 Restore degraded peatlands wherever feasible where sources of polluted water have been removed or abated.

Strategy 6. Control invasive exotic plants

Some peatlands types have been invaded by exotic plants that are transforming the composition, structure and function of peatland vegetation. The impacts are most widespread and severe in in Montane Swamp Complex Community (Vic), Montane peatlands and swamps (NSW), Carex Sedgeland (NSW), with more localised invasions in Blue Mountains swamps (NSW) and Alpine bogs and fens (EPBC, Vic, ACT). The following actions are priorities in those communities.

6.1 Undertake regular (annual/biennial) surveillance for transformer weed species across the range of the relevant communities to identify priority sites for pre-emptive weed control.

6.2 Implement appropriate weed control measures that avoid or minimise collateral impacts on native vegetation.

6.3 Develop and implement readiness plans for weed control to exploit suitable conditions for control within 12-18 months of fire occurrence.

Strategy 7. Control invasive animals

Invasive animals disrupt soils and vegetation structure of some peatland types, most notably horses, pigs, deer in Alpine bogs and fens (EPBC, ACT, Vic), pigs and deer in Montane peatlands and swamps (NSW), pigs and deer in Montane Swamp Complex Community (Vic), and pigs in Carex Sedgeland (NSW). Priority actions for these communities include the following.

7.1 Regular monitoring of invasive animal populations in peatland landscapes using appropriate designs and methods such as scat surveys, aerial surveys, etc.

7.2 Regular control of populations using appropriate levels of culling, trapping, or other appropriate methods.

7.3 Restoration of degraded peatlands using appropriate methods (see 4.3).

Strategy 8. Control access by vehicles and pedestrians

Even infrequent use of vehicles or occasional pedestrian access can disrupt vegetation structure and soil structure and stability in peatlands. Uncontrolled access is most prevalent in Montane Swamp Complex Community (Vic), Montane peatlands and swamps (NSW), Carex Sedgeland (NSW), with more localised degradation in Coastal upland swamps (NSW), Blue Mountains swamps (NSW), Newnes plateau shrub swamps (NSW) and Alpine bogs and fens (EPBC, Vic, ACT).

8.1 Use planning instruments and other mechanisms to avoid routing of vehicular tracks, services easements and walking tracks through, or within a 50 m buffer of peatlands.

8.2 Implement appropriate access management (e.g. track redirection or closure of tracks, signage, fencing, etc.) to reduce or prevent disturbance from vehicles or pedestrians.

Strategy 9. Restore eroded and hydrologically degraded sites

Erosion and sedimentation in peatlands results from primary causes such as channelised runoff from denuded or disturbed catchments, or from disruption of vegetation or surface soils by vehicles, people or domestic or feral animals. The impacts are most widespread and severe in Montane Swamp Complex Community (Vic), Montane peatlands and swamps (NSW), Carex Sedgeland (NSW), with more localised degradation in Blue Mountains swamps (NSW) and Alpine bogs and fens (EPBC, Vic, ACT). The following actions are priorities in those communities.

9.1 Undertake appropriate stabilisation works to remove or neutralise the cause of erosion and sedimentation in peatlands.

9.2 Where feasible, restore peatlands degraded by erosion or sedimentation with appropriate surface stabilisation, water management, revegetation and/or weed control.

Cross-cutting Strategy 10. Undertake research and monitoring

Strategies 1-8 require a reliable evidence base to inform the design and methods of management actions, to evaluate the performance of alternative actions, and to adapt them progressively as the knowledge base evolves (Williams 2011). The following actions are priorities to inform conservation and management of peatland ecosystems.

10.1 Undertake research to improve understanding the role of of hydrological processes, feedbacks and dependencies in maintaining the function and diversity of peatland ecosystems.

10.2 Undertake research to improve understanding the role of fire regimes, feedbacks and dependencies in maintaining the function and diversity of peatland ecosystems.

10.3 Undertake research to project responses of peatland function and diversity ecosystems to alternative climate scenarios.

10.4 Undertake research to quantify the contribution of peatland ecosystems to services such as maintenance of stream flows, maintenance of water quality, carbon sequestration, etc.

10.5 Undertake research to inform underground coal mine designs compatible with sustainable peatland function and maintenance of peatland biodiversity.

10.6 Undertake research to improve performance of techniques for restoration of peatland vegetation, fauna, soils and hydrological function.

Cross-cutting Strategy 11. Communicate and educate about the values and roles of peatland ecosystems

The uniqueness, values and sensitivity of Australian peatlands are not widely known across the community, industry and government sectors. The following strategies will help improve awareness and appreciation of Australian peatland ecosystems.

11.1 Develop and implement a communications plan to meet the information requirements of a range of partners and stakeholders and raise awareness in the general public.

11.2 Develop education and extension materials for targeted audiences within communities, land managers and businesses with a stake in the sustainability of peatland ecosystems.

11.3 Regularly disseminate outputs of peatland research, monitoring and management through research literatures, meetings, social and traditional media.

Cross-cutting Strategy 12. Engage community in conservation action

Conservation action is most effective when local communities are engaged in their development, implementation and outcomes. Community engagement also helps to attract resources and other support to undertake essential work. The following strategies will help realise these benefits for Australian peatlands.

12.1 Provide opportunities for local Indigenous community engagement in implementation of biodiversity conservation, while supporting connection to country.

12.2 Develop and maintain relationships with key partners in the community and business sectors, and key land managers.

12.3 Engage local community groups in development and implementation of strategies 1 -11.

12.4 Promote interaction and sharing of knowledge and resources across a network of community groups working in different peatland ecosystems.

12.5 Work with partners and stakeholders to identify and secure funding to support implementation of actions.

Healthy post-fire regrowth of a Morton-Penrose shrub swamp, 12 months after fire. Postfire flowering of Xanthorrhoea resinosa *occurs in the winters following summer fires and provides an important winter food source for small mammals and birds in the early post-fire environment, as do the seeds of sedges such as* Lepidosperma limicola*. Tianjara plateau, Morton National Park, NSW. Image: D. Keith.*

Discussion and Conclusions

The 2019-20 bushfires had a range of impacts that varied between different rainforest and peatland ecosystem types, primarily through interactions with other processes. Our analyses have highlighted exposure to threats from interactions between fire and pre-fire drought, with projections for increased duration and severity of drought into the future. However, our diagnostic models illuminate a range of other threats, such as vegetation clearing and fragmentation, invasive plants, animals and diseases, nutrient enrichment, erosion and sedimentation and hydrological disruption by mining, many of which also interact with fire to increase risks of ecosystem degradation and collapse. The threat diagnosis enabled the design of suite of strategies to reduce risks to rainforest and peatland ecosystems.

A workable typological framework is fundamental to evidence-based ecosystem management (Keith 2015; Keith et al. 2015), yet progress in Australia is hampered by legacies of differing classification systems that developed largely independently in each state and territory jurisdiction. The only available framework for national synthesis (the National Vegetation Information System) is based on traditional vegetation mapping concepts that are largely unsuitable for ecosystem risk assessment and management. As well, listings of threatened ecological communities have been based on different methods for defining and assessing ecosystems. Our study demonstrates how function-based typologies can be developed and applied to Australian ecosystems, with working units for national synthesis defined for rainforests and peatlands based on contrasting ecological traits and processes and contrasting levels of data availability. The proposed working units may in some cases be coarser than optimal units for ecosystem assessment and management, but the working classifications establish a foundational framework, consistent with international standards and cross-referenced to existing listings, that paves the way for a comprehensive and systematic risk assessment of two major groups of terrestrial ecosystems. Rainforests and peatlands are critically important for biodiversity, given their unique biota, and for sustaining Australian economies, societies and cultures, given their contributions to diverse ecosystem services.

The working typologies have identified at least 14 broad rainforest ecosystem units and 11 broad peatland units within southeastern Australia that show contrasting compositional features, occur in different environments and have different syndromes of threats. These broad units nest within internationally adopted ecosystem functional groups and establish hierarchical relationships between state-based classification schemes and Threatened Ecological Communities listed under state, territory and Commonwealth legislation. For the first time, these typologies provide a systematic context for ecological communities that have been assessed and listed at national level, in relation to those that are yet to be assessed including some that appear eligible for future listing. The typologies also point to where better alignment between state and Commonwealth listings could be achieved.

The function-based typological framework developed here for rainforests and peatland ecosystems enabled a systematic diagnosis of major threatening processes in diagrammatic models that placed the threats of key ecosystem components and processes (Figs. 2 & 3). We identified 12 and 11 inter-related threats, respectively, to rainforests and peatlands. Of these, climate-change related threats were pervasive throughout both groups of ecosystems, reflecting the relatively marginal and increasingly unsuitable climatic conditions for their persistence on the Australian continent. Shifting fire regimes are closely linked to climate change, with evidence suggesting particular sensitivity of both rainforests and peatlands to interactions between climate and fire through droughts of increasing duration and intensity. Other types of threats are having markedly differential impacts on different types of rainforests and peatlands (Tables 6 & 9), including land clearing and fragmentation, weed invasions, feral vertebrate invasions, pollution and soil degradation, disease and underground mining. The generic diagnostic models thus enable a modular analysis of threats to specific ecosystem types within broader rainforest and peatland functional groups.

Finally, the development of diagnostic models established a deductive framework for risk reduction strategies that address each threat syndrome identified in Tables 6 and 9. In addition to climate change mitigation, we identified eight risk-reduction strategies for rainforests and nine strategies for peatlands, with each strategy comprising multiple actions. Three cross-cutting strategies relating to research, communication and community engagement inform and support the implementation of the risk-reduction strategies.

The risk-based approach developed here for fire-affected rainforests and peatlands in southeastern Australia is applicable to systematic assessment and management of all ecosystem types and threatening processes, supporting progress toward United Nations Sustainable Development Goals.

Recommendations

1. Refine the working typologies for rainforests and peatland ecosystems, by incorporating additional data sources, analyses and expert review, to extend coverage beyond southeastern Australia, develop a finer level of classification within the broadly defined units, and develop detailed descriptions of the units.
2. Develop distribution maps for rainforest and peatland types defined in the respective typologies.
3. Carry out national-scale risk assessments of rainforest and peatland ecosystems using international standards (IUCN 2016), as adopted in-principle by Australian governments under the Common Assessment Method (CAM) Agreement.
4. Implement ecosystem conservation strategies described within this report.
5. Extend the diagnostic risk-based approach developed for rainforests and peatlands to the assessment and management of other Australian ecosystem types, including eucalypt forests, heathlands, grasslands wetlands, savannas and deserts.

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