EYES ON RECOVERY

A large-scale collaborative camera survey initiative tracking the recovery of Australian wildlife after the 2019/20 bushfires

Consolidated Analysis
2024
WildObs Report to WWF-Australia

WildObs

The Wildlife Observatory, or WildObs, is housed by the Terrestrial Ecosystem Research Network (TERN) and the University of Queensland. WildObs is dedicated to bringing together Australia's camera trap data through collaboration to enable long-term large-scale monitoring and providing rapid analyses and data visualisation.

WWF-Australia

WWF is an independent conservation organization, with over 30 million followers and a global network active in nearly 100 countries. Our mission is to stop the degradation of the planet's natural environment and to build a future in which people live in harmony with nature, by conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

Acknowledgements

Eyes on Recovery surveys were conducted on the land of the Gugu-Badhun, Agwamin, Yuggera, Bundjalung, Gumbainggir, Biripi, Geawegal, Wonnarua, Dharug, Eora, Kuring-gai, Yuin, Ngarigo, Bidwell, Wiradjuri, Jaitmatang, Ngarigo and Kurnai peoples. We acknowledge the Traditional Custodians of these lands and their continuing connection to land, water and culture. We pay our respects to their Elders – past, present and emerging.

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Citation

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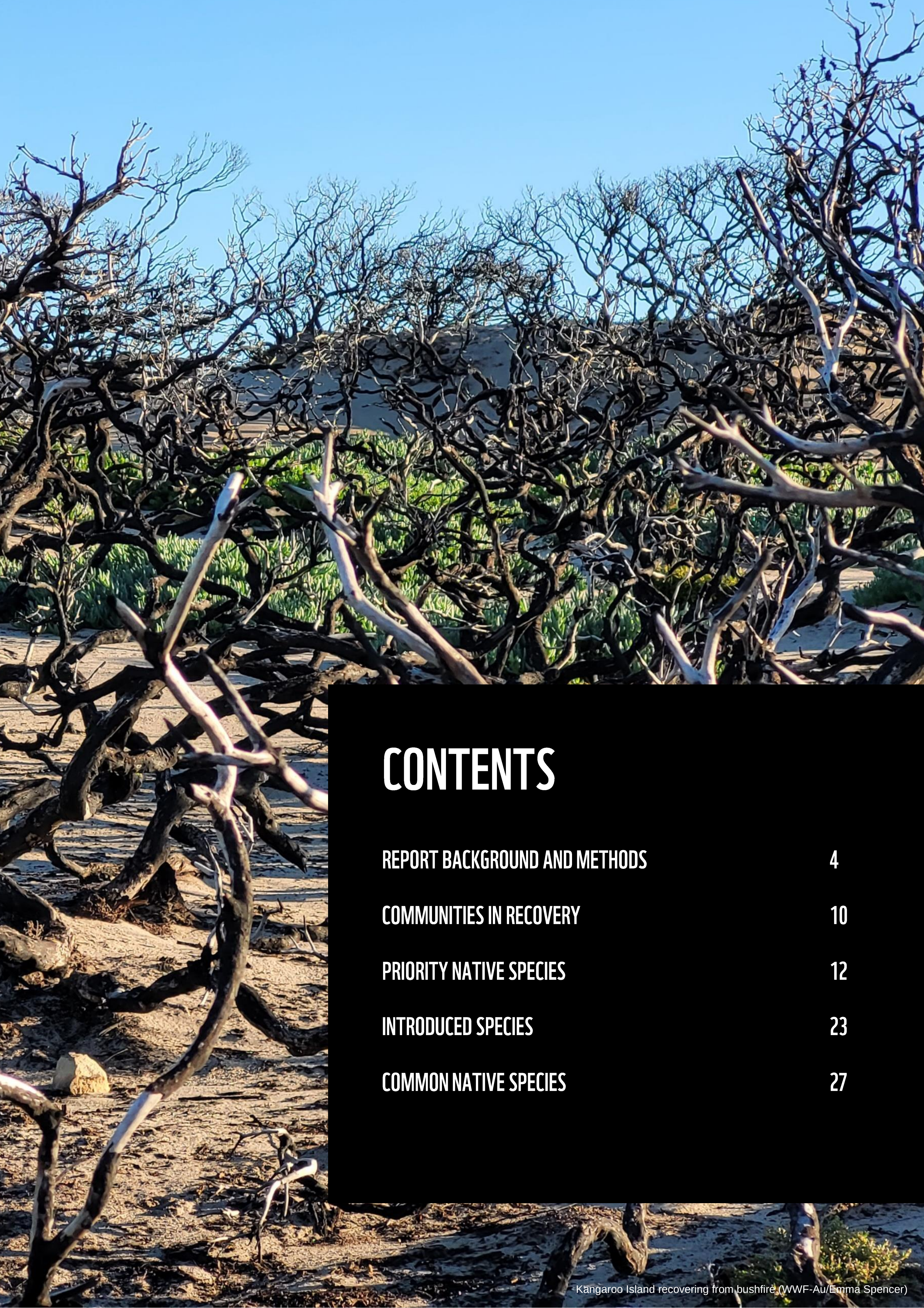
Cover photographs: Collection of images captured by Eyes on Recovery wildlife cameras



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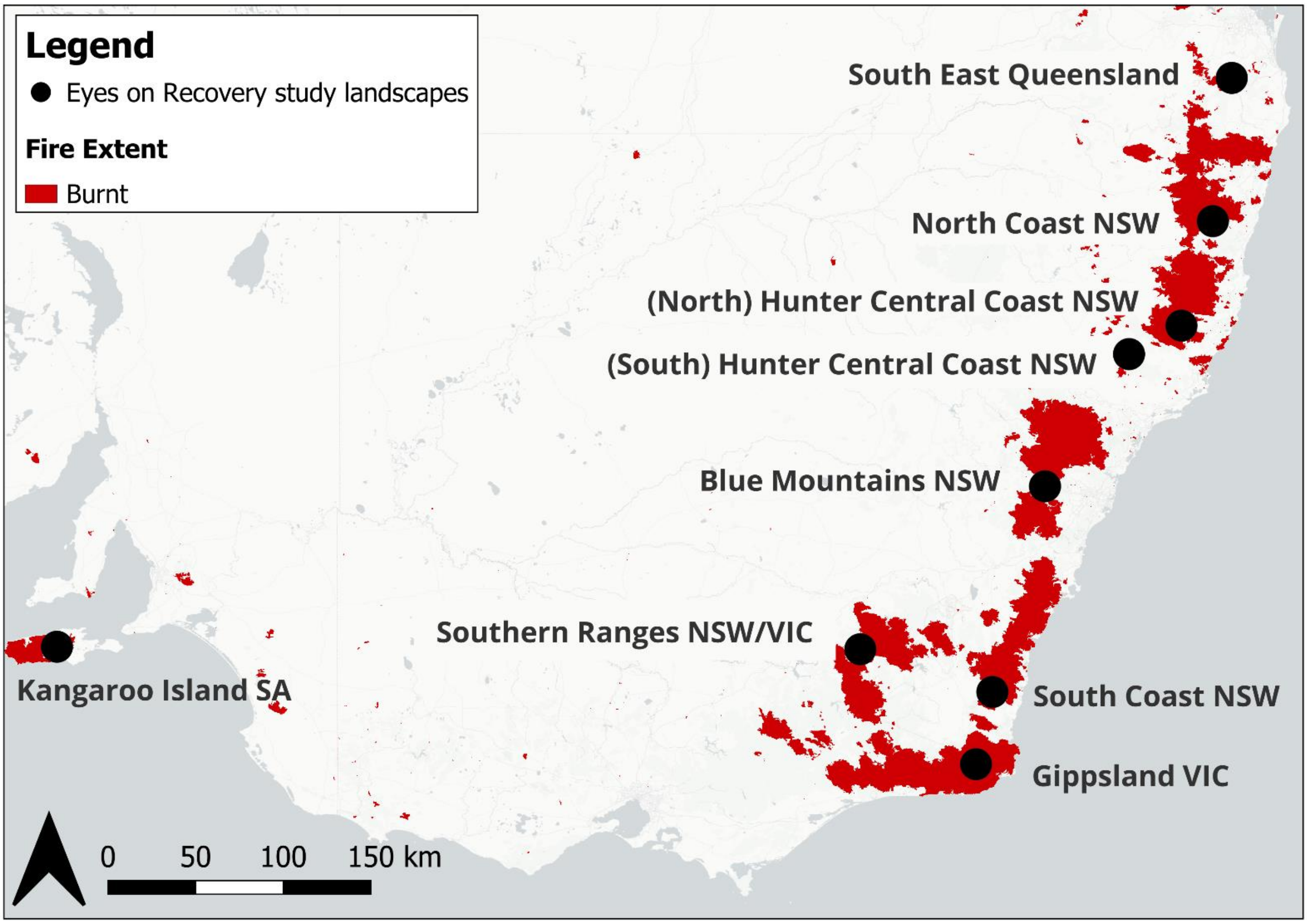


Figure 1.1. The nine Eyes on Recovery landscapes overlaid over fire extent (red) across south-eastern Queensland, New South Wales, Victoria and South Australia across the 2019-20 Australian bushfire season

The 2019-2020 summer mega-fires burned more than 10 million hectares across south-eastern Australia, killing or displacing an estimated 3 billion animals. Eyes on Recovery investigated these bushfire impacts, tracking the recovery of key threatened animals in a range of fire-impacted environments. This involved use of over 1,100 wildlife cameras deployed across 9 distinct landscapes (**Figure 1.1**) and 17 unique surveys in eastern Australia resulting in the collection of more than 8.5 million images. The design of each survey was partner-led and focused on answering pressing local management questions. Therefore, a variety of different camera trap methods were used across the project.

Collating and analysing large survey datasets with non-standardised camera trap methods can be difficult but 'big data' modelling approaches help to address some of these challenges. To apply these modelling approaches and analyse the many datasets, Eyes on Recovery collaborated with the Wildlife Observatory (WildObs). WildObs is hosted by Australia's Terrestial Ecosystem Research Network (TERN) and The University of Queensland and has the overarching goal of addressing pressing wildlife questions with robust data and analysis tools[1].

WildObs consolidated the Eyes on Recovery survey datasets and then applied several different methods to visualise, analyse and understand data collected across the project. This report presents an overview of these methods, and the results produced as part of this consolidated analysis.

ANALYSIS METHODS

Thirteen of the 17 Eyes on Recovery surveys were included in this consolidated analysis (see **Table 1.1** for the specific surveys and survey methods used). Surveys were selected based on a number of factors, including the number of camera units used and the duration of monitoring. Surveys that monitored very

[1] Terrestrial Ecosystem Research Network. 2024. WildObs Australia. Available from: https://www.tern.org.au/wildobs/

Table 1.1. Surveys included in the consolidated data analysis. Includes details on the landscape grouping, the number of cameras deployed, the approximate duration of camera deployment and the average effort per camera (i.e. the average number of days each camera was active). Numbers under 'Method' indicate the specific method used, with 1= lured/not lured cameras at 0.5m above ground in environment, 2 = cameras targeting roads, 3= cameras on drift-line fences, 4 = not lured cameras at 1m above ground, 5 = cameras set up on wombat burrows, 6 = cameras set up in brush-tail rock wallaby specific habitat.

Landscape	No. cameras	Duration	Av. effort per camera	Survey names	Method type
South-east QLD	61	18 months	293	South-East Queensland Post-Fire Fauna Survey	1
North Coast	82	24 months	203	North-Eastern New South Wales Brush-Tailed Rock Wallaby Monitoring Project	6
				North-Eastern New South Wales Potoroo and Parma Wallaby Monitoring Project	1
Hunter Central Coast (North)	41	8 months	135	Threatened Macropods Survived the Catastrophic 'Black Summer' Bushfires	1
Hunter Central Coast (South)	35	15 months	119		
Blue Mountains	171	24 months	196	Blue Mountains Post-Megafire Recovery Survey	4
				Can Ecosystems Recover Under a Changing Wildfire Regime in the Greater Blue Mountains World Heritage Area?	1
				Post-Fire Evaluation of Critical Weight Range Mammals in the Greater Blue Mountains World Heritage Area	1
South Coast	148	12 months	74	Nungatta Threatened Native Mammal and Invasive Predator Post-Fire Monitoring	2
				South East Forest Long-Footed Potoroo Post-Fire Survey	1
Southern Ranges	247	18 months	243	Impacts of the 2019-20 Summer Bushfires on Terrestrial Species in the Foothill Forests of South-Eastern Australia	1
				Wombat-Powered Recovery: Harnessing an Ecosystem Engineer to Increase Bushfire Resilience	1,5
Gippsland	100	12 months	275	Southern Ark Predators & Priority Species Project	1,2
Kangaroo Island	100	26 months	454	Kangaroo Island Dunnart Project	1,3

specific habitat features like artificial refuges (including nest boxes and hollows) were excluded from the consolidated analysis.

Data from the 13 surveys from 9 landscapes were combined and then explored using a variety of different methods. These included: **species accumulation curves**, which were used to visualise differences in mammalian and avian species richness across the 9 landscapes and to evaluate survey effort, **encounter rate maps**, which helped to spatially represent differences in the frequency of each species encountered on cameras across the 9 landscapes, and **occupancy models**, which were used to show species trends over time and assess relationships with key environmental variables like fire, habitat, anthropogenic impacts, rainfall, and elevation. These methods are outlined in detail below.

SPECIES ACCUMULATION CURVES

Species accumulation curves (or species discovery curves) are a well-known technique in ecology for estimating the total number of species that can be detected in an area (**Figure 1.2**). They can be used to examine whether search effort for species richness was sufficient and to estimate the number of additional species that could be detected with further effort. They can also be used to visualise and compare species richness across different locations and taxonomic groupings (e.g. mammals versus birds).

Curves show the accumulation of newly detected species (on the y-axis) as search effort (x-axis) increased. The rate of increase generally slows as effort is increased. A curve that has levelled out to a horizontal line indicates that all detectable species in an area have been detected. In the context of Eyes on Recovery, this refers to all species that could be detected using camera traps. Species accumulation curves for each Eyes on Recovery landscape were separated out for the most commonly detected taxon groups, mammals and birds. The solid lines (marked observed) show the species accumulation curve plotted from the camera data in each landscape. The dashed lines (marked extrapolated) project these curves forward to estimate the number of additional species that could be detected with more camera monitoring effort.

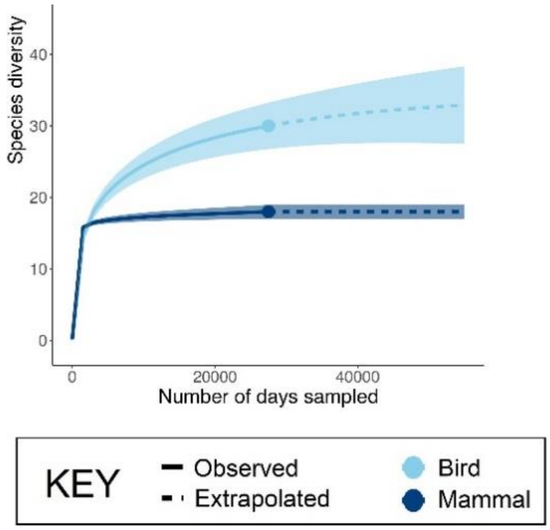


Figure 1.2. Species accumulation curve for bird and mammal species.

ENCOUNTER RATE MAPS

Encounter rates are an indication of species activity in an area adjusted by the amount of monitoring effort. Encounter rates were calculated for each landscape by first summing the total number of independent detections of a species across the landscape. Detections of the same species in photos taken at the same site were considered independent when they had at least a 30-minute interval between them. The number of independent detections was then divided by the total number of days of camera monitoring in the landscape, which is the sum of days across all cameras [2].

Encounter rates are a useful simple measure of a species' relative abundance or activity in different areas, especially when mapped to visualise the data (**Figure 1.3**). However, encounter rates do not account for imperfect detection (i.e. an animal is present in the environment and not detected), nor adjust for how differences in survey methods at different locations (e.g., camera placement or baiting) will affect the encounter rate of species. In the example below, the yellow dots indicate where a species is detected in a landscape (in the Gippsland, Kangaroo Island and South Coast landscapes). The size of the circles and the numbers then indicate the encounter rate for this species (in this case, the species is encountered at the greatest rate in the Gippsland landscape). Red crosses indicate landscapes where the species was not recorded (in this case, 6 landscapes).

To visualise whether priority species were being detected in every landscape where they are potentially present, we included a species habitat or occurrence map for each priority species, hatched in green in the example figure below.

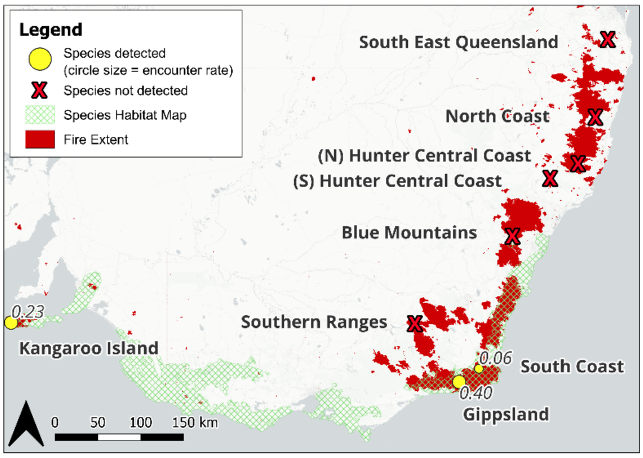


Figure 1.3. Encounter rate map for a single species.

For threatened species, we used the Australian federal government's Species of National Environmental Significance maps and included all categories where species do, are likely to, or may have habitat[3]. For the superb and albert's lyrebirds (not threatened) and koala (not threatened across its full distribution), we used publicly available observational point data from the Atlas of Living Australia[4] to create occurrence maps. We screened these points for outliers by comparing with existing range maps for the species and then used ArcGISPro to aggregate points within 200km into a polygon.

OCCUPANCY MODELS

Occupancy refers to the proportion of camera sites occupied by a species given that it may not be detected at every site where it is present. Occupancy models have two parts, one formula for species detectability assuming it is there, and one that provides an estimate of occupancy accounting for imperfect detection. This two-part modelling process controls for how each species detection probability is affected by differences in survey methods (e.g. baiting) and other variables (e.g. set of roads or in the bush). Occupancy is generally related to abundance as well as how animals move and are distributed across an area[2]. For example, if there is the same distribution of detections for both a solitary species and a group-living species, these could have the same occupancy. However, since each detection of the group-living species has more than one individual, abundance could be very different. Occupancy models are a well-established method for analysing camera trap data to examine species trends

[2] Rovero F. & Spitale D., 2016 Species-level occupancy analysis, in Camera Trapping for Wildlife Research, eds Rovero F and Zimmermann F, Pelagic Publishing
[3] Australian Government Department of Climate Change, Energy, the Environment and Water. Species of National Environmental Significance and selected marine and cetacean species. Available from: https://fed.dcceew.gov.au/datasets/036d137b6de7429cb0bd796424f7406c_0/explore
[4] Atlas of Living Australia. n.d..Available from: https://www.ala.org.au/

and to assess how environmental variables influence species[2].

Occupancy was estimated using hierarchical occupancy models implemented in the R package 'unmarked'. Models were run for every species with more than 30 independent detections across all Eyes on Recovery data. We explored how both detection probability and occupancy changed over time and were influenced by several environmental and methodological variables. The methodological covariates included whether a lure was used with the camera, and environmental variables included fire, habitat type, anthropogenic impacts, rainfall and elevation. We extracted environmental variables by overlaying camera coordinates with spatial layers and calculated the average or modal variable in 1km, 3km, 5km and 10km buffers around each camera. Before running occupancy models, we spatially resampled the detection histories by grouping nearby cameras into same-sized gridcells to account for differences in camera spacing between the 13 surveys. This also helps account for individual animals that may be detected across multiple nearby camera locations (particularly if that animal is highly mobile or if the cameras were positioned close together). Data was spatially resampled by overlaying hexagons across the landscapes at five scales: the exact camera location, and with a radius of 1km^2, 3km^2, 5km^2, and 10km^2 around the camera locations.

For species occupancy models, the grid size and covariate extraction scale were chosen to match each species' home range size (**Table 1.2**). Mammal home range sizes were sourced from a global database[5]. Due to uncertainty around bird species home ranges, we used a default value of 3km^2.

To examine changes in occupancy through time, we partitioned the Eyes on Recovery data into three-month periods (quarters) and calculated separate occupancy estimates for each quarter. As in the example below (**Figure 1.4**), estimates of occupancy are shown with dots, with lines representing 95% uncertainty. The timing and duration of each survey in Eyes on Recovery varied, meaning that survey effort was not constant through time. While this was accounted for in the model estimates, we calculated species occupancy only for the quarters that had sufficient data collected across several surveys: from Apr-Jun 2021 to Jul-Sep 2022. In addition, for individual species, we removed any quarters where there were not enough detections to obtain a reliable occupancy rate estimate for that species.

Table 1.2. Summary of the different home range sizes used for each species in this analysis.

Species	Home range scale applied (km^2)
Spotted-tailed quoll (*Dasyurus maculatus*)	10
Koala (*Phascolarctos cinereus*)	3
Brush-tailed rock wallaby (*Petrogale penicillata*)	1
Southern brown bandicoot (*Isoodon obesulus obesulus*)	1
Parma wallaby (*Notamacropus parma*)	1
Long-nosed potoroo (*Potorous tridactylus*)	1
Superb lyrebird (*Menura novaehollandiae*)	3
Red-legged pademelon (*Thylogale stigmatica*)	1
Kangaroo Island dunnart (*Sminthopsis aitkeni*)	1
Albert's lyrebird (*Menura alberti*)	3
Long-footed potoroo (*Potorous longipes*)	1
Red fox (*Vulpus vulpus*)	10
Feral cat (*Felis catus*)	10
Feral pig (*Sus scrofa*)	10
European rabbit (*Oryctolagus cuniculus*)	1
Eastern grey kangaroo (*Macropus giganteus*)	3
Red-necked wallaby (*Notamacropus rufogriseus)*	1
Swamp wallaby (*Wallabia bicolor*)	1
Red-necked pademelon (*Thylogale thetis)*	1
Long-nosed bandicoot (*Perameles nasuta)*	1
Northern brown bandicoot (*Isoodon macrourus)*	1
Common wombat (*Vombatus ursinus)*	1
Short-beaked echidna (*Tachyglossus aculeatus)*	3
Small mammal species (<500g)	1
Possum species	1

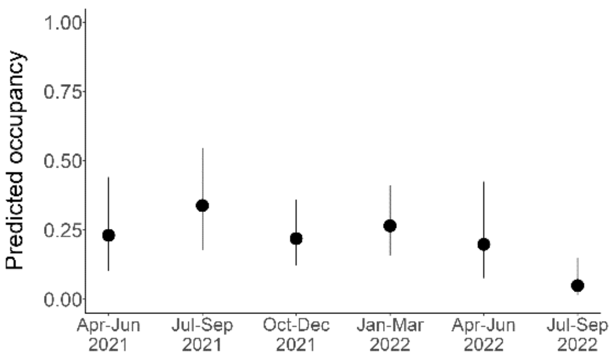


Figure 1.4. Example graph of occupancy through time.

[5] Broekman et al. 2022 HomeRange: A global database of mammalian home ranges. Global Ecology and Biogeography https://doi.org/10.1111/geb.13625

MODEL SELECTION

We sought to understand if and how species recovered from fire and to determine which environmental variables influence occupancy. We ran multiple models and used the Akaike Information Criterion (AIC) to find the models that best fit the data. AIC scores are commonly used in statistics to assess model fit, with a lower AIC indicating a better-fitting model. AIC scores are calculated based on how well the model fits the data and the model complexity. Simpler models are preferred over more complex models to avoid overfitting models to random fluctuations in the data rather than explaining underlying patterns.

For each species, we compared a set of competing occupancy models with various covariates. For each set of variables, we included linear, additive, and synergistic relationships between environmental variables (**Table 1.3**). We first assessed methodology-related variables in the detection formula to determine the most influential variables describing detection probability. Methodology-related variables included method type as in **Table 1.1**, camera brand, whether the camera is on a trail, bait (if used), and number of active cameras at the site. We then incorporated the best detection formula in models exploring which environmental variables best described occupancy. For both modelling steps we initially implemented univariate models, and if there were multiple competing variables <4 AIC from the lowest AIC score, we then implemented multivariate models using the competing variables. The only exception was for the Kangaroo Island dunnart, parma wallaby, red-necked pademelon, southern brown bandicoot, feral pig, and western grey kangaroo, where we used <2 AIC as a threshold due to too many competing variables when using <4 AIC, preventing models from completing. We considered additive (+) and synergistic relationships (*) and only allowed a maximum of two variables to be considered in a multivariate model. We then took all the univariate and multivariate models forward to a final model selection for each species.

For the final model selection, we considered the best fitting models to be within 2 AIC of the lowest AIC score. For each priority species, we summarised the best fitting models using colours to represent environmental variables and symbols to represent the direction of the linear relationship (**Figure 1.5; Table 1.3**).

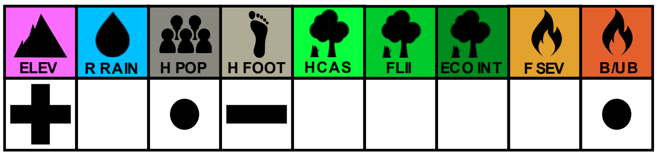


Figure 1.5. Example representation of top models. Plus and minus signs indicate variables with significant positive or negative relationships with occupancy, respectively. Circles indicate variables with no significant relationship with occupancy. See **Table 1.3**. for further details on symbol meanings.

Table 1.3. Summary of the different environmental variables examined during model selection.

Variable	Symbol	Description	Year	Resolution	Source
Elevation	ELEV	Ground-level elevation in meters.	2008	250m	Hutchinson et al. 2008. GEODATA 9 second DEM and D8: Digital Elevation Model Version 3 and Flow Direction Grid 2008. Commonwealth of Australia (Geoscience Australia). Available from: https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/66006
Recent average rainfall	R RAIN	Average monthly precipitation during the post-fire and monitoring period (March 2020 – September 2022).	2023	~5km (0.05 degrees)	Australian Bureau of Meteorology. 2023. Recent and historical rainfall maps. Available from: http://www.bom.gov.au/climate/maps/rainfall/
Human population	H POP	Estimated residential population based on census data.	2022	1km	Australian Bureau of Statistics. 2022. Australian population grid 2022 in ESRI Grid format. Available from: https://www.abs.gov.au/statistics/people/population/regional-population/2021-22#data-downloads
Human footprint	H FOOT	Combines 8 variables measuring direct and indirect human pressures on the environment, including built environments, population density, electric infrastructure, crop lands, pasture lands, roads, railways and navigable waterways.	2009	1km	Venter et al. 2016.Global terrestrial Human Footprint maps for 1993 and 2009. *Scientific Data*. **3**: 160067. doi:10.1038/sdata.2016.67. Data available from: www.worldpop.org/data/
Habitat Condition Assessment System (2001-2018) base model	HCAS	Estimate of habitat condition for terrestrial biodiversity over the period (2001-2018), ranging from 0 (habitat completely removed) to 1.0 (habitat in reference condition).	2001-2018	~250m (9 arcseconds)	Harwood et al. 2021. 9 arcsecond gridded HCAS 2.1 (2001-2018) base model estimation of habitat condition for terrestrial biodiversity, 18-year trend and 2010-2015 epoch change for continental Australia. v7. CSIRO. Data Collection. Available from: https://doi.org/10.25919/nkjf-f088
Forest Landscape Integrity Index	FLII	An index of forest integrity as determined by degree of anthropogenic modification. Integrates data on observed and inferred forest pressures and lost forest connectivity.	2020	1km	Grantham et al. 2020. Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. Nature Communications 11: 5978. https://doi.org/10.1038/s41467-020-19493-3. Data available from: https://www.forestintegrity.com/download-data
Ecoregion intactness	ECO INT	A metric that captures habitat loss, habitat quality, and fragmentation effects.	2009	1km	Beyer et al. 2020. Substantial losses in ecoregion intactness highlight urgency of globally coordinated action. Conservation Letters 13:e12692. https://doi.org/10.1111/conl.12692. Data available from: https://doi.org/10.14264/uql.2019.773.
Fire severity	F SEV	The Australian Google Earth Engine Burnt Area Map (GEEBAM) rapidly assessed severity of the 2019-2020 fires from satellite data. We consolidated severity categories into three groupings: "unburnt", "low/moderate" and "high/very high". The unburnt category includes any points outside the extent of or categorised as "no data" in GEEBAM.	2019-2020	40m	GEEBAM Fire Severity dataset available from: https://fed.dcceew.gov.au/maps/erin::aus-geebam-fire-severity-dataset-2019-2020/explore
Burnt/ Unburnt	B/UB	GEEBAM severity data consolidated into two groupings: "burnt" and "unburnt". The unburnt category includes any points outside the fire extent or categorised as "no data" in GEEBAM.	As above	As above	As above.

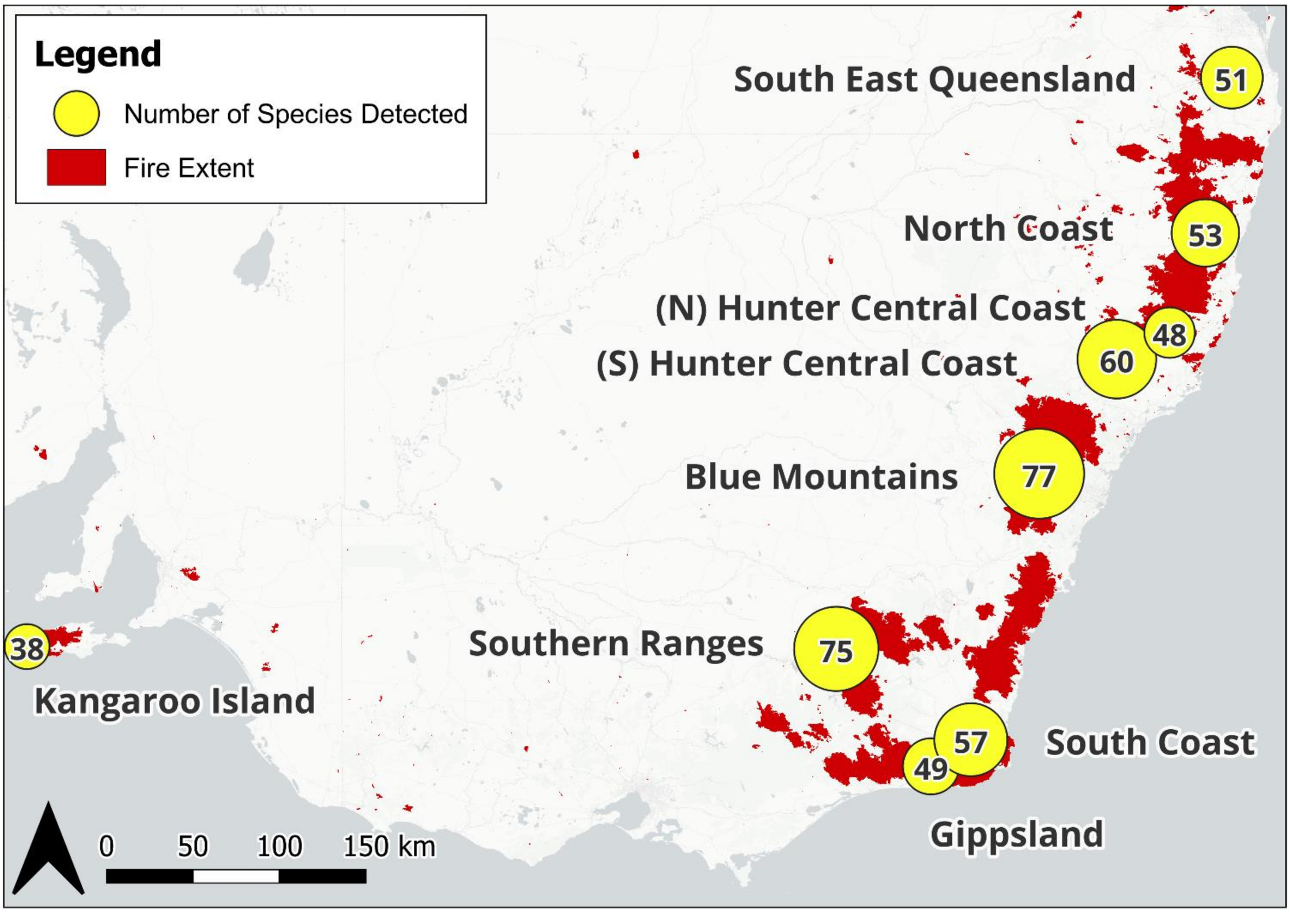


Figure 2.1. The number of species detected across the 9 Eyes on Recovery landscapes in south eastern Australia, overlaid with fire extent

Across all landscapes, 151 species were detected and identified. This included 133 native and 18 introduced species. Of the native species detected, 54 were mammals (including 6 listed as Endangered and 4 listed as Vulnerable on the federal Environmental Protection and Biodiversity Conservation (EPBC) Act), 89 were birds (including 1 listed as Vulnerable on the EPBC Act), and 8 were reptiles.

The landscape with the highest number of species detected was the Blue Mountains NSW with 77 species, and then the Southern Ranges NSW/VIC with 75 species (**Figure 2.1**). This is unsurprising, as these landscapes also had the most cameras deployed over longer periods of time and these numbers were not scaled by monitoring effort (i.e. number of days the cameras were active). We plotted species accumulation curves to understand the potential effects that differences in monitoring effort have on detected species richness across the landscapes (**Figure 2.2**).

For mammals, the species accumulation curves generally indicated that the amount of camera effort in each landscape was sufficient to detect almost all mammal species. Further, when just examining the number of mammal species detected across landscapes, results were consistent with approximately 20 mammal species detected per landscape. The exceptions were Kangaroo Island and (South) Hunter Central Coast NSW, where <15 and >30 mammalian species were detected across the surveys, respectively. This may reflect real differences in mammal diversity, or a difference in the detectability of mammal species by cameras within different landscapes. For example, there is a lower diversity of mammalian species found on Kangaroo Island compared to much of mainland Australia.

The species accumulation curves for birds show that the amount of camera effort applied did not detect all bird species in each landscape. This observation is unsurprising, as camera monitoring is generally considered a good method for detecting mammals and ground-dwelling birds, but often has poor results for most flighted bird species (although specific methods like lures can be used to increase detection of these animals). Further, camera placement and survey designs implemented for Eyes on Recovery were generally targeted towards ground-based species rather than flighted birds.

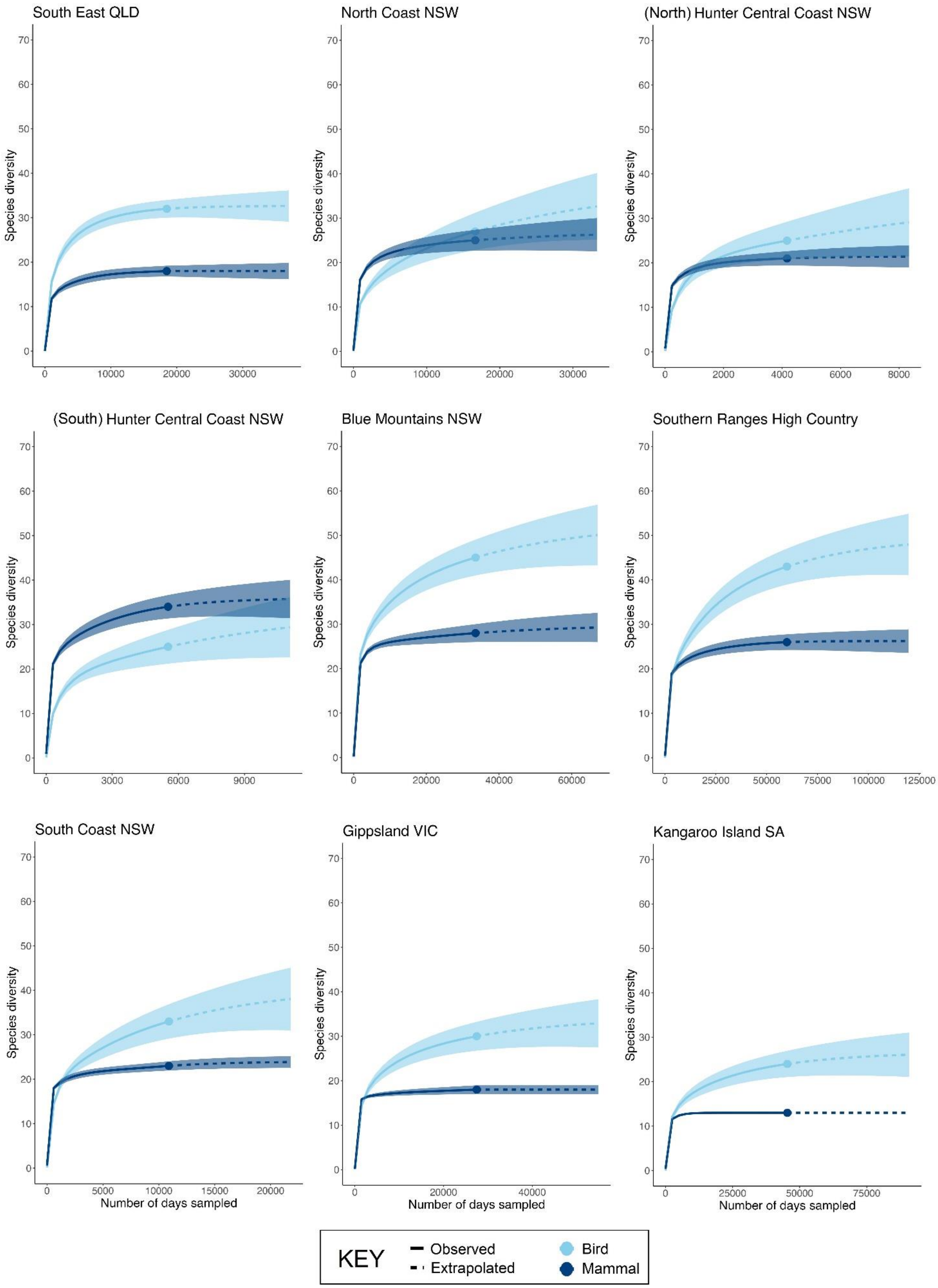


Figure 2.2. Species accumulation curves by taxon group for each Eyes on Recovery landscape. Only bird and mammal groups were analysed as few reptiles or amphibians were captured on camera and data likely underrepresented these species.

PRIORITY NATIVE SPECIES

These native species were highlighted by Eyes on Recovery on-ground project partners as priorities for monitoring and management. Each species was also included on the Australian federal government's **list of animals requiring urgent monitoring and management intervention** following the 2019-20 bushfires[6]. These priority species were selected based on the extent of their habitat burnt by the bushfires, their current listing (e.g. as vulnerable, endangered or critically endangered) as of 2019-20, and any physical, behavioural and ecological vulnerabilities to fire identified.

SPOTTED-TAIL QUOLL

(*Dasyurus maculatus*)

KOALA

(*Phascolarctos cinereus*)

BRUSH-TAILED ROCK WALLABY

(*Petrogale penicillata*)

SOUTHERN BROWN BANDICOOT

(*Isoodon obesulus*)

PARMA WALLABY

(*Notamacropus parma*)

LONG-NOSED POTOROO

(*Potorous tridactylus*)

SUPERB LYREBIRD

(*Menura novaehollandiae*)

RED-LEGGED PADEMELON

(*Thylogale stigmatica*)

KANGAROO ISLAND DUNNART

(*Sminthopsis aitkeni*)

ALBERT'S LYREBIRD

(*Menura alberti*)

LONG-FOOTED POTOROO

(*Potorous longipes*)

[6] Wildlife and Threatened Species Bushfire Recovery Expert Panel. 2020. Provisional list of animals requiring urgent management intervention. Available from: https://www.dcceew.gov.au/environment/biodiversity/bushfire-recovery/bushfire-impacts/priority-animals

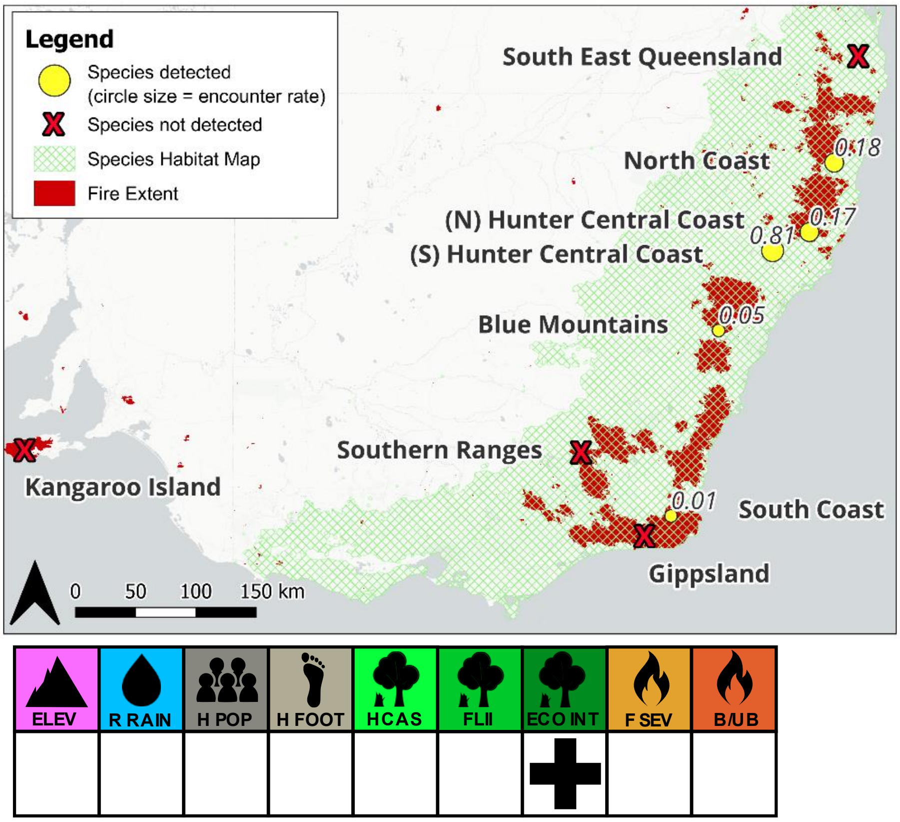


Figure 3.1. Map of spotted-tail quoll encounter rates overlaid with fire extent and quoll habitat range; numbers show rounded encounter rates (top). Top models predicting the effects of different variables on quoll occupancy (bottom).

The spotted-tail quoll subspecies *Dasyurus maculatus maculatus* is distributed along the east coast of Australia from central Queensland in the north to Victoria and Tasmania. The south-east mainland population of *Dasyurus maculatus maculatus* is listed as Endangered under the federal Environmental Protection and Biodiversity Conservation (EPBC) Act, while the Tasmanian population is listed as Vulnerable. All Eyes on Recovery landscapes except Kangaroo Island were within the range of the south-east mainland population of *Dasyurus maculatus maculatus*, which had approximately 27% of its habitat burnt in the 2019/20 fires[7].

KEY FINDINGS

- Spotted-tail quolls were detected in a total of 100 independent events across 5 of the 8 Eyes on Recovery landscapes within their range, with the highest encounter rate recorded in the South Hunter Central Coast landscape and the lowest rate recorded in the South Coast landscape (with only a single detection; **Figure 3.1**).
- Occupancy estimates across the six study quarters indicate relatively stable quoll numbers through time, although there was insufficient data to estimate an occupancy rate in the Jan-Mar 2022 quarter (**Figure 3.2**).
- Ecoregion intactness was the only important variable predicting spotted-tail quoll occupancy, showing a positive and significant trend with increasing occupancy (**Figure 3.1, 3.2**). Both fire variables were more important than the null model, but neither revealed any strong relationships with quoll occupancy.

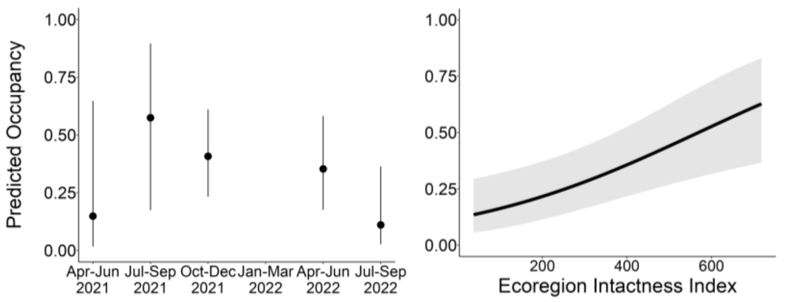


Figure 3.2. Spotted-tail quoll occupancy plotted against time (left), and with ecoregion intactness (right). Error bars and shading show 95% confidence intervals. The solid line indicates a significant ($P < 0.05$) relationship.

[7] Ward, et al. Impact of 2019–2020 mega-fires on Australian fauna habitat. Nature Ecology & Evolution 4.10 (2020): 1321-1326.

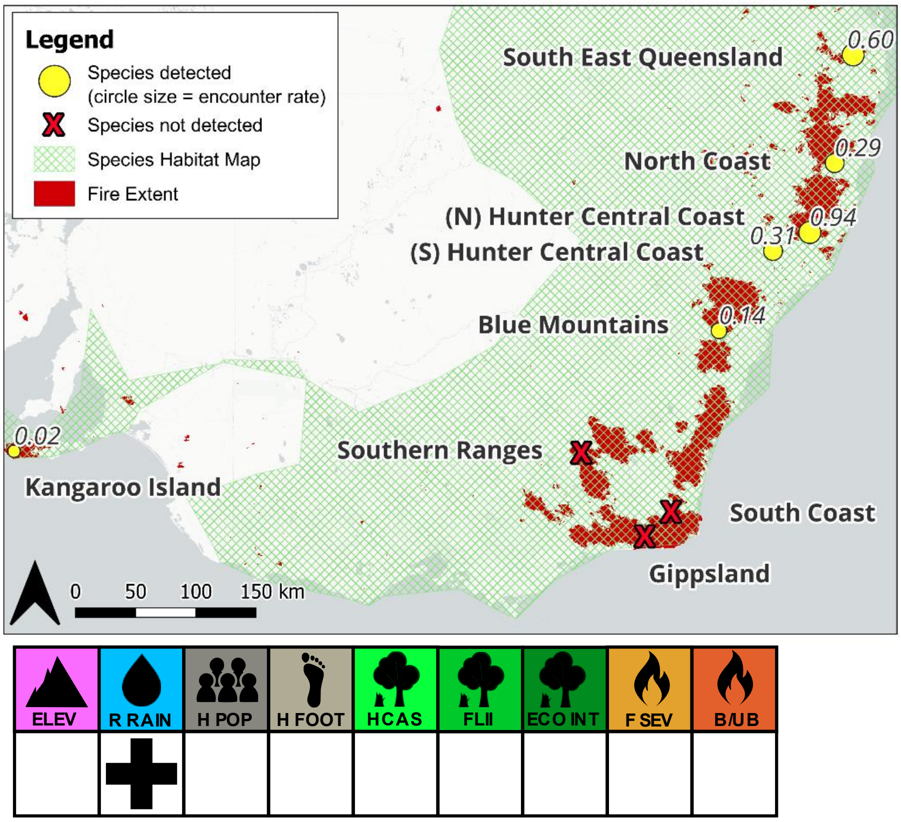


Figure 3.3. Map of koala encounter rates overlaid with fire extent and koala habitat range; numbers show rounded encounter rates (top). Top models predicting the effects of different variables on koala occupancy (bottom).

Koalas have a wide-ranging distribution across eastern Australia, from central Queensland south to Victoria as well as a small area of eastern South Australia. Populations in Queensland, New South Wales (NSW) and the Australian Capital Territory are listed as Endangered under the federal EPBC Act. Approximately 11% of habitat with listed koala populations was burnt in the 2019/20 megafires[6]. As a specialised herbivore they may be particularly impacted by forest canopy loss caused by severe fires[5].

KEY FINDINGS

- Koalas were detected in 6 of the 9 Eyes on Recovery landscapes within their range, with the highest encounter rates observed in North Central Hunter Coast and south-east Queensland and with no koalas detected in the Southern Ranges, South Coast and Gippsland landscapes (**Figure 3.3**).
- There was a small increase in koala occupancy following the Oct-Dec 2021 quarter, although koala detection data was limited during the first two quarters making occupancy estimates during this time harder to predict (**Figure 3.4**).
- Recent average rainfall was identified as the most important factor influencing koala occupancy and had a significant positive relationship with occupancy (i.e. sites recording higher recent average rainfall also recorded higher koala occupancy; **Figure 3.3, 3.4**).
- Fire severity and burnt/unburnt variables were not included in the top models, and while both fire-related variables were considered more important factors than the null model for predicting occupancy, neither had significant effects on koala occupancy.

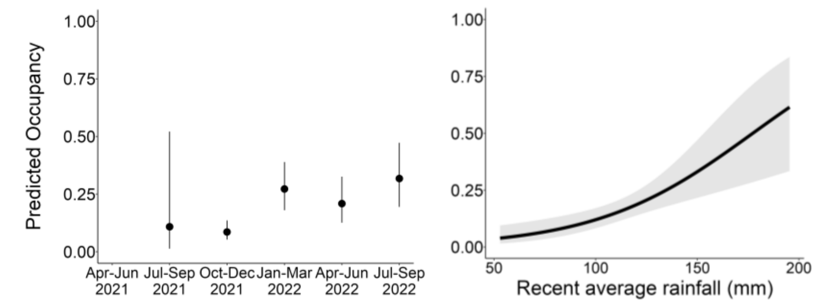
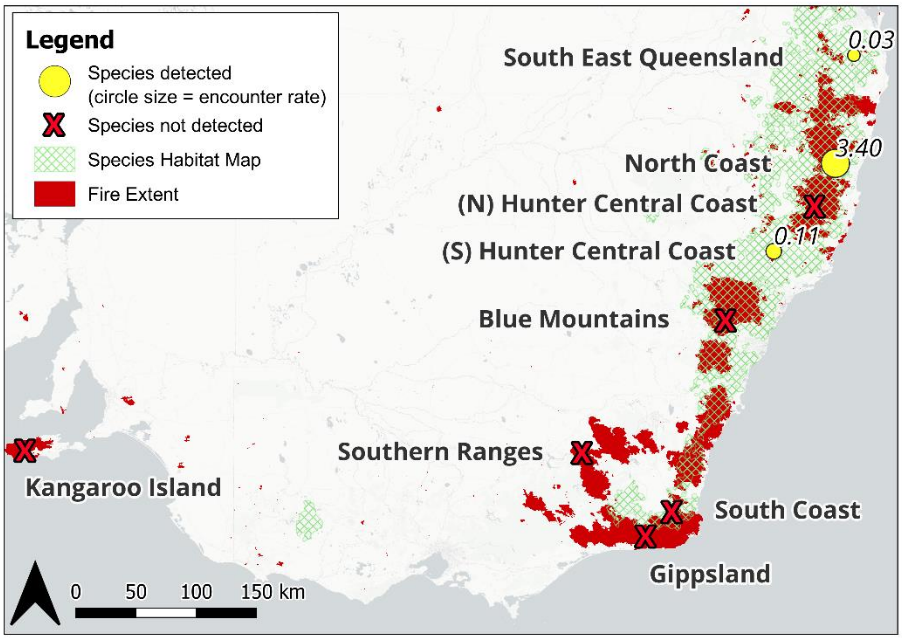


Figure 3.4. Koala occupancy plotted against time (left), and with recent average rainfall (right). Error bars show 95% confidence intervals. The solid line for the recent average rainfall indicates a significant positive ($P < 0.05$) relationship.

BRUSH-TAILED ROCK WALLABY (*Petrogale penicillata*)



ELEV	R RAIN	H POP	H FOOT	HCAS	FLII	ECO INT	F SEV	B/UB
●							●	

Figure 3.5. Map of brush-tailed rock wallaby encounter rate overlaid with fire extent and rock wallaby habitat range; numbers show rounded encounter rates (top). Top models predicting the effects of different variables on rock wallaby occupancy (bottom).

Brush-tailed rock wallabies are listed as Vulnerable under the EPBC Act. They have a broad distribution along the east coast of Australia, from south-east Queensland to southern NSW. However, within this distribution they persist in small colonies and have very specific habitat requirements – rocky areas with crevices and caves for shelter. Their distribution has decreased 50-90% since European colonisation and many remaining colonies are now isolated due to forest fragmentation[8]. Approximately 38% of their habitat range was burnt in the 2019/20 fires[6]. As large herbivores, brush-tailed rock wallabies are particularly susceptible to vegetation loss from fire and to the impact of introduced herbivores[5].

KEY FINDINGS

- Brush-tailed rock wallabies were detected in 3 of 9 Eyes on Recovery landscapes, with the highest encounter rate recorded in the North Coast landscape where cameras targeted rocky areas of likely habitat (**Figure 3.5**). There were 2 landscapes within their broad distribution where they were not detected, including the North Hunter Central Coast and the Blue Mountains landscapes but in both locations, cameras were not set up to specifically target this species.
- There were not enough detections to estimate occupancy rates for brush-tailed rock wallabies through time.
- Fire severity and elevation were both important variables predicting brush-tailed rock wallaby occupancy, but no significant relationships were observed (**Figure 3.5, 3.6**).

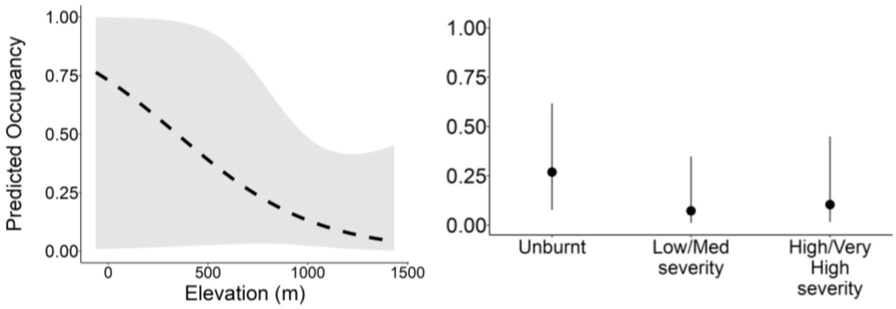


Figure 3.6. Brush-tailed rock wallaby occupancy with elevation (left) and for each fire severity category (right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

[8] Australian Government Department of Agriculture, Water and the Environment 2021. Conservation Advice for Petrogale penicillate (Brush-tailed Rock Wallaby). Available from: https://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=225

SOUTHERN BROWN BANDICOOT (*Isoodon obesulus obesulus*)

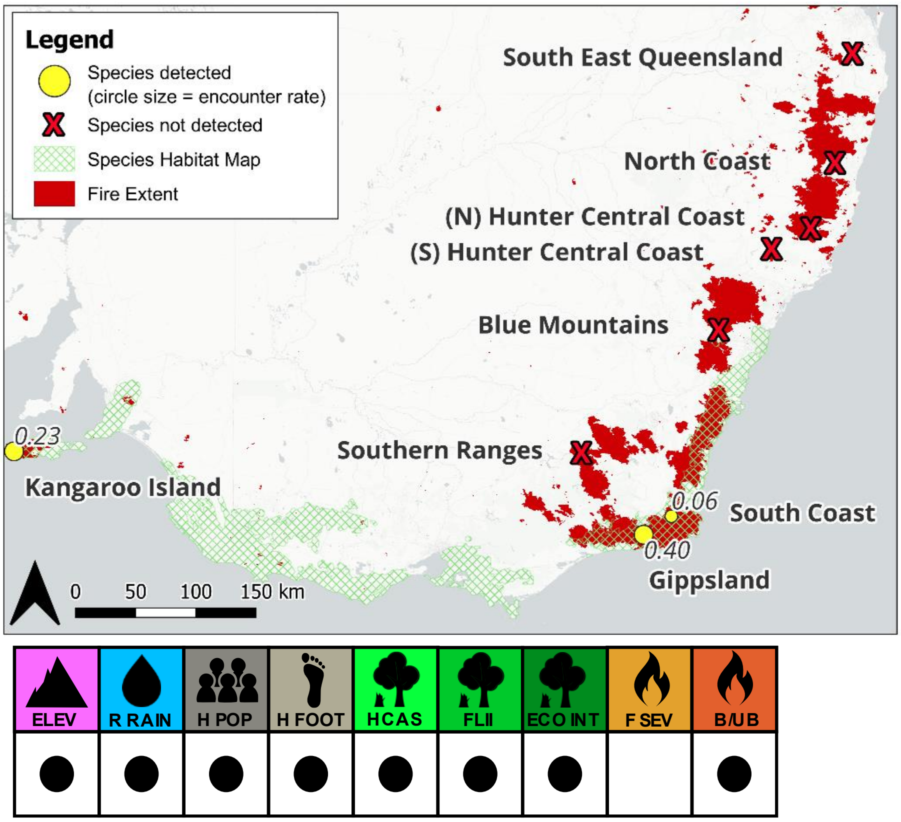


Figure 3.7. Map of southern brown bandicoot encounter rate overlaid with fire extent and bandicoot habitat range; numbers show rounded encounter rates (top). Top models predicting the effects of different variables on bandicoot occupancy (bottom).

The southern brown bandicoot subspecies *Isoodon obesulus obesulus* is listed as Endangered and is found in south-eastern South Australia, southern Victoria, and south-eastern NSW. As small ground-dwelling marsupials, southern brown bandicoots require high density vegetation to shelter from predators and have been found to be severely impacted by fox and cat predation in post-fire landscapes[9]. Approximately 25% of their habitat was burnt in the 2019-20 bushfires[6].

KEY FINDINGS

- Southern brown bandicoots were detected in all 3 Eyes on Recovery landscapes within their range, with the highest encounter rate in Gippsland, Victoria (**Figure 3.7**).
- Southern brown bandicoot occupancy was similar across time, although it was significantly lower in the last (Jul-Sep 2022) period than in the first four quarters of monitoring (**Figure 3.8**).
- All variables except for fire severity were considered equally important in influencing bandicoot occupancy (**Figure 3.7**), although none of the relationships between occupancy and these variables were significant (**Figure 3.8**). Both fire variables were more important than the null model, however bandicoot occupancy did not vary across either burnt and unburnt sites or fire severity.

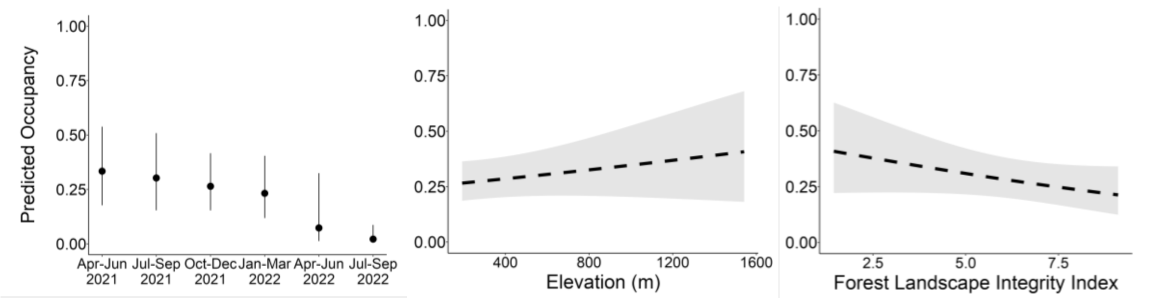


Figure 3.8. Southern brown bandicoot occupancy over time (left), with elevation (middle) and forest landscape integrity (right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

[9] Threatened Species Scientific Committee, 2016. Conservation Advice for *Isoodon obesulus obesulus*. Available from: https://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=68050

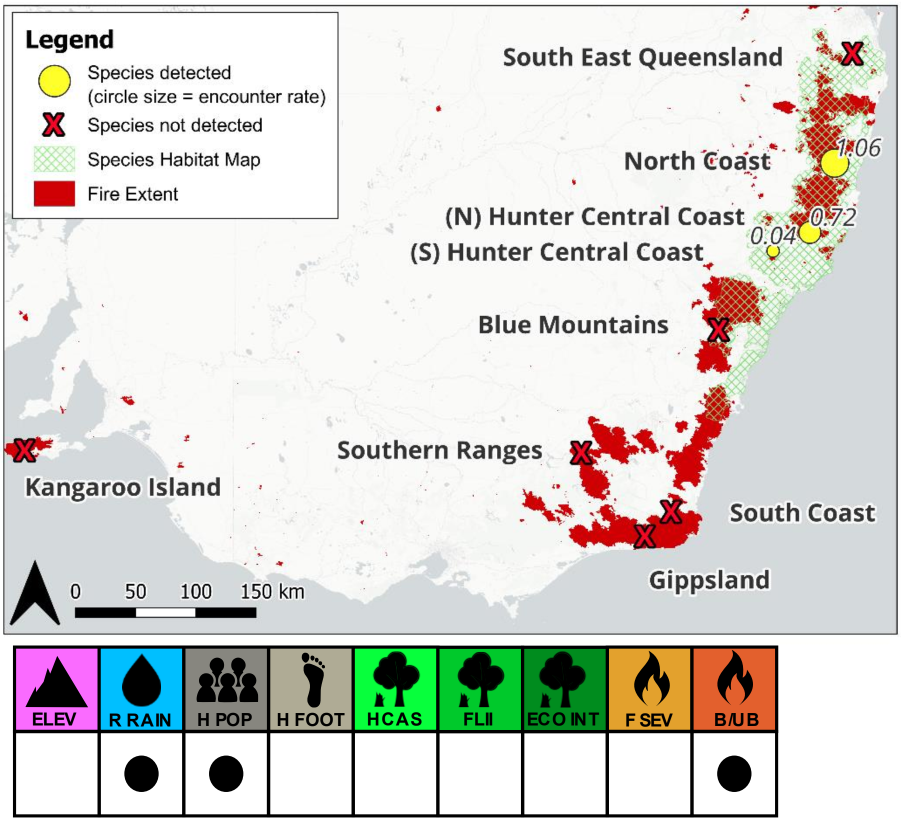


Figure 3.9. Map of parma wallaby encounter rate overlaid with fire extent and wallaby habitat range; numbers show rounded encounter rates (top). Top models predicting the effects of different variables on wallaby occupancy (bottom).

Parma wallabies are found along the east coast of Australia from south-east Queensland down to mid NSW. They were not listed as threatened species under the EPBC Act at the time of the 2019/20 fires, but have since been listed as Vulnerable. Parma wallabies experience mortality during and after fires due to their limited ability to flee, their specialised habitat requirements and their reliance on dense forest understorey to hide from predators[10]. Approximately 59% of their habitat was burnt during the 2019/20 fires, resulting in an estimated population decline of 24% the following year[9].

KEY FINDINGS

- Parma wallabies were detected in 3 of 9 Eyes on Recovery landscapes, with the highest encounter rate in the North Coast landscape (**Figure 3.9**).
- Average parma wallaby occupancy rates varied by quarter, with substantial uncertainty around the occupancy estimates meaning there were no significant differences between quarters (**Figure 3.10**Figure).
- The burnt/unburnt fire variable, human population and average recent rainfall were identified as important drivers of parma wallaby occupancy, however none of these variables appeared to have significant effects (**Figure 3.9, 3.10**).

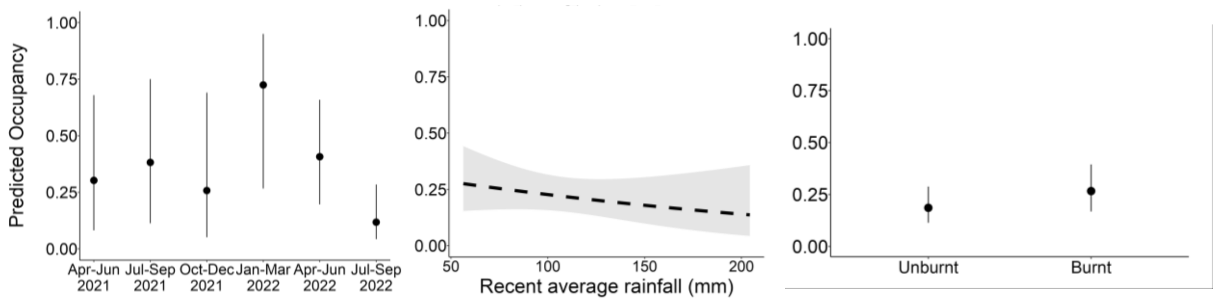


Figure 3.10. Parma wallaby occupancy over time (left), with recent average rainfall (middle) and for each fire category (right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

[10] Australian Government Department of Climate Change, Energy, the Environment and Water 2022. Conservation Advice for *Notamacropus parma* (Parma Wallaby). Available from: https://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=89289

LONG-NOSED POTOROO (*Potorous tridactylus*)

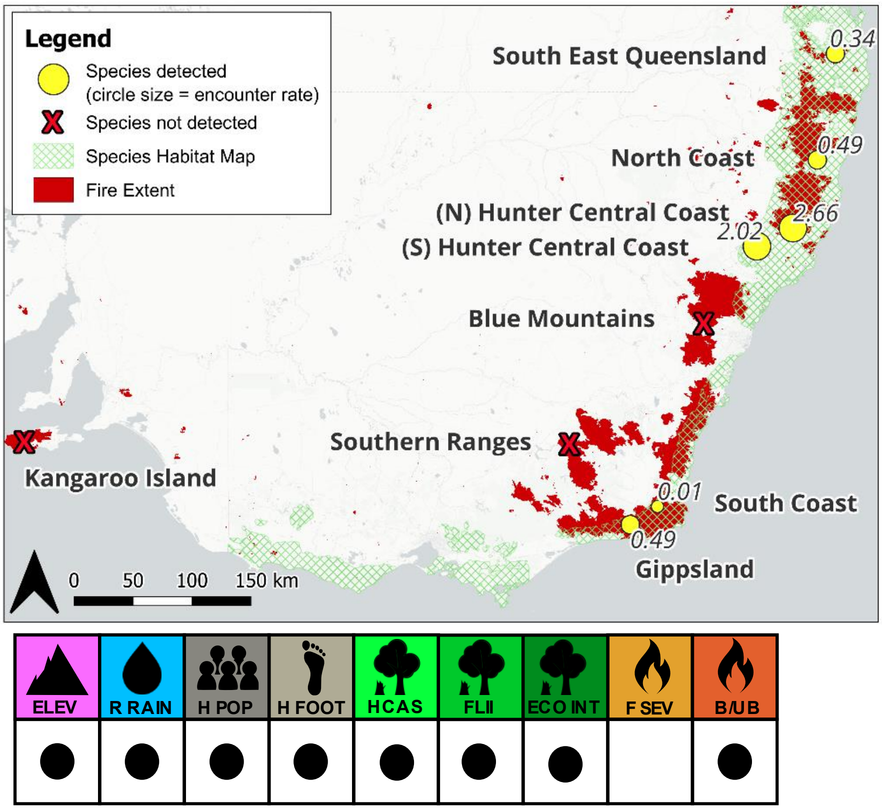


Figure 3.11. Map of long-nosed potoroo encounter rate overlaid with fire extent and potoroo habitat range, numbers show rounded encounter rates (top). Top models predicting the effects of different variables on potoroo occupancy (bottom).

Long-nosed potoroos have three subspecies.The northern mainland subspecies *Potorous tridactylus tridacylus* occurs on the east coast of Australia between central Queensland and the Sydney basin in NSW. The southern mainland subspecies *Potorous tridactylus trisulcatus* occurs south of the Sydney basin and around the southern coast of Victoria. *Potorous tridatylus apicalis* occurs on Tasmania and the islands of the bass strait. The Eyes on Recovery landscapes were within the ranges of the mainland subspecies, which are both listed as Vulnerable under the EPBC Act. Long-nosed potoroo are vulnerable to post-fire predation, and often prefer long unburnt (+20 years) patches of forest[11].

KEY FINDINGS

- Long-nosed potoroos were detected in 6 Eyes on Recovery landscapes, with the highest encounter rates in the Hunter Central Coast NSW landscapes (**Figure 3.11**).
- Long-nosed potoroos show relatively stable occupancy over time (**Figure 3.12**).
- All variables except for fire severity were identified as equally important for predicting long-nosed potoroo occupancy but in all cases, these trends were not statistically significant (**Figure 3.11, 3.12**).

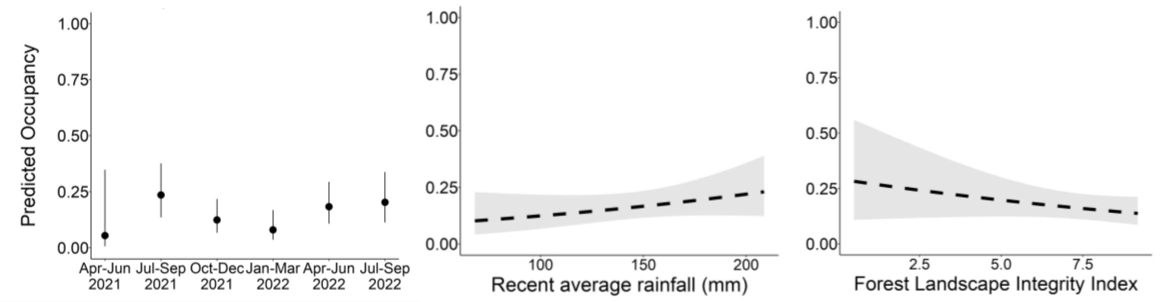


Figure 3.12. Long-nosed potoroo occupancy over time (left), across different average recent rainfall (middle), and with increasing forest landscape integrity (right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

[11] Australian Government Department of Climate Change, Energy, the Environment and Water 2022. Conservation Advice for *Potorous tridactylus trisulcatus* (southern long-nosed potoroo). Available from: https://www.environment.gov.au/biodiversity/threatened/species/pubs/86367-conservation-advice-02032022.pdf

SUPERB LYREBIRD (*Menura novaehollandiae*)

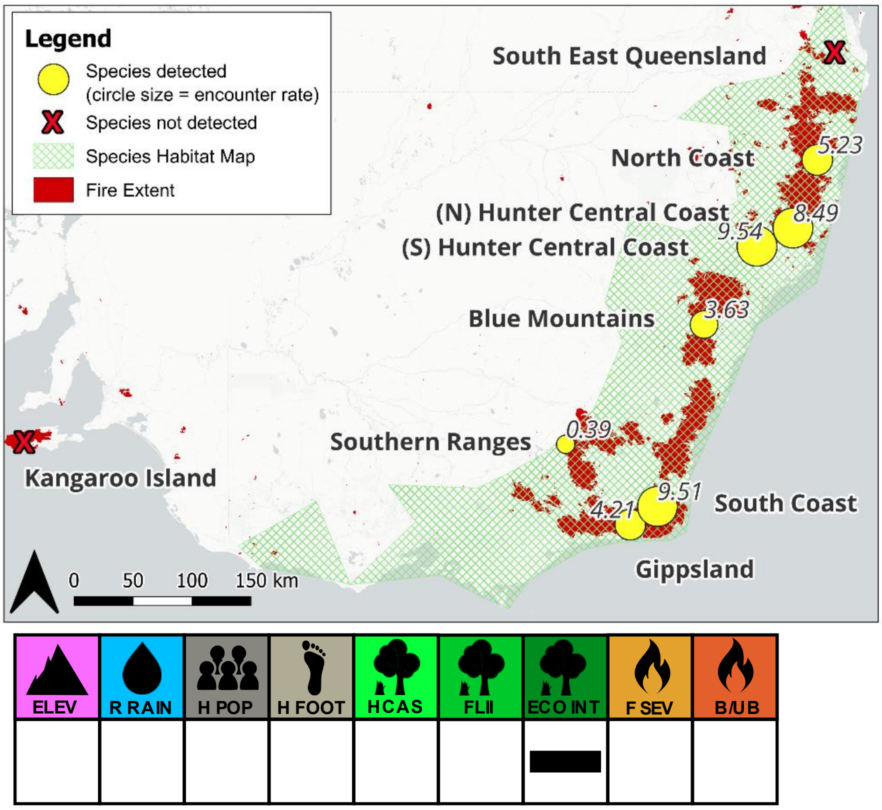


Figure 3.13. Map of superb lyrebird encounter rate overlaid with fire extent and lyrebird habitat range; numbers show rounded encounter rates (top). Top models predicting the effects of different variables on lyrebird occupancy (bottom).

Superb lyrebirds occur along the east coast of Australia from south-east Queensland to southern Victoria, and Tasmania. While they are not listed as threatened, they were identified by the Australian government as a priority species for management intervention following the 2019/20 fires due to the overlap between their range and the fire extent and a high predicted fire mortality rate[5]. Superb lyrebirds are ground dwelling, roosting in trees at night. While they are best known for their expert song mimicry, they are also known as 'ecosystem engineers' for the huge amounts of soil and leaf litter they move around the forest looking for food, increasing plant germination rates[12].

KEY FINDINGS

- Superb lyrebirds were found in every Eyes on Recovery landscape except Kangaroo Island and South East Queensland (although Albert's lyrebird *Menura alberti* was detected at several sites in the South East Queensland landscape), with the highest rates recorded in the South Coast and the two Hunter Central Coast landscapes (**Figure 3.13**).
- Lyrebird occupancy showed no significant variation across time (**Figure 3.14**).
- Ecoregion intactness was the only identified important factor driving occupancy, with occupancy decreasing with ecoregion intactness (**Figure 3.13**). Both fire variables were not considered important drivers of occupancy, although they were more important than the null model.

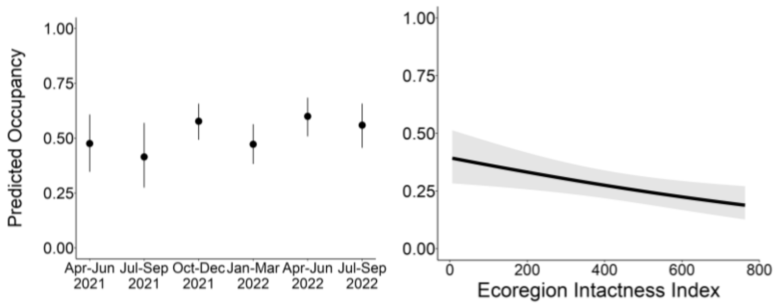


Figure 3.14. Superb lyrebird occupancy over time (left) and ecoregion intactness (right). Error bars show 95% confidence intervals and solid line indicates a significant (P < 0.05) relationship between variables.

[12] Maisey et al. 2022. Differential effects of ecosystem engineering by the superb lyrebird *Menura novaehollandiae* and herbivory by large mammals on floristic regeneration and structure in wet eucalypt forests. Ecology and Evolution 12(6): e8956.

RED-LEGGED PADEMELON (*Thylogale stigmatica*)

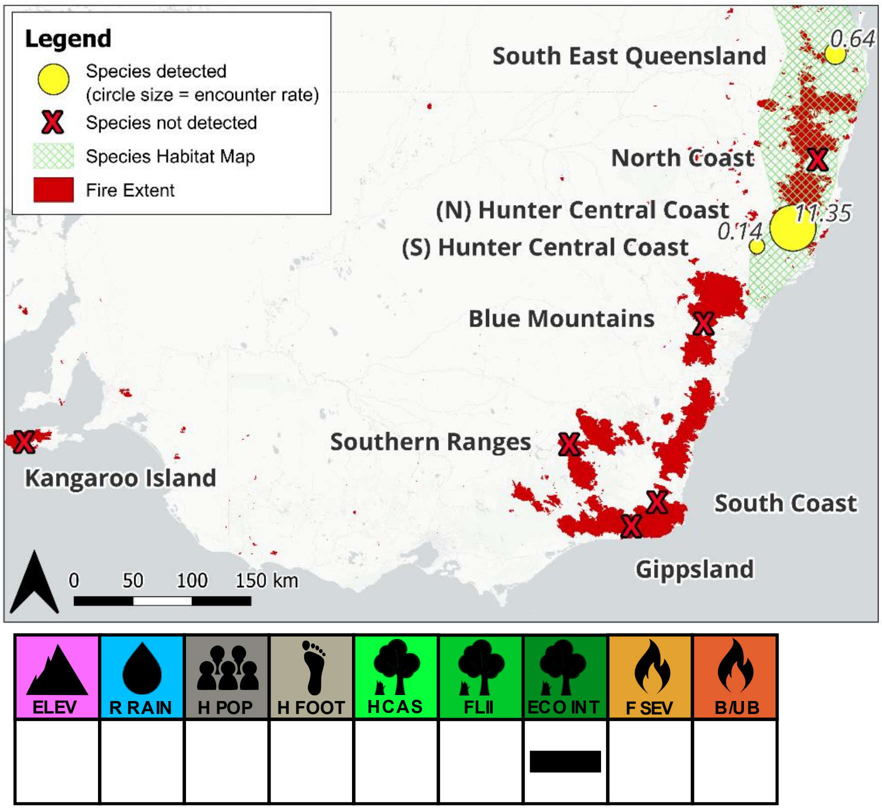


Figure 3.15. Map of red-legged pademelon encounter rate overlaid with fire extent and pademelon habitat range, numbers show rounded encounter rates (top). Top models predicting the effects of different variables on pademelon occupancy (bottom).

Red-legged pademelons are patchily distributed along the eastern Australia coast from the tip of Cape York Peninsula in Queensland to around Tamworth in New South Wales. This species is also found in New Guinea. While it is not listed as threatened under the EPBC Act, it is listed as vulnerable in New South Wales (NSW)[13]. Red-legged pademelons are threatened by inappropriate fire regimes that reduce or degrade their habitat. They are particularly threatened by overly frequent or intense fires and regular burning of forest edges. Red-legged pademelons may also be threatened by predation in post-fire habitats by their native predators, dingoes, and by introduced predations including red foxes (*Vulpes vulpes*) and feral cats (*Felis catus*).

KEY FINDINGS

- Red-legged pademelons were encountered in three Eyes on Recovery landscapes, with most records occurring in the Hunter Central Coast sites (**Figure 3.15**).
- Occupancy rates for the red-legged pademelon indicated relative stability through time (**Figure 3.16**).
- Only ecosystem intactness was identified as important in driving occupancy (**Figure 3.15)**, with pademelon occupancy decreasing with increasing ecoregion intactness (**Figure 3.16**).

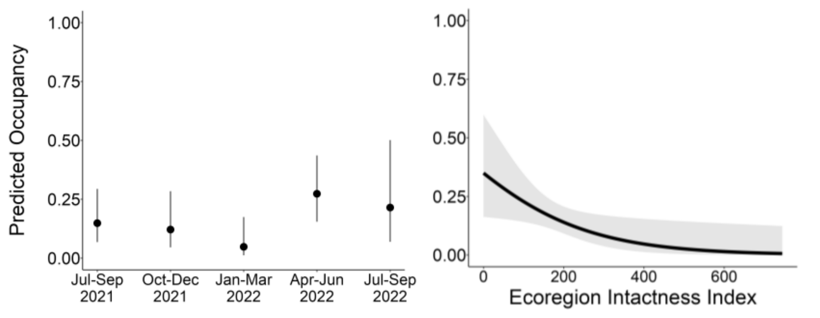


Figure 3.16. Red-legged pademelon occupancy over time (left), with increasing ecoregion intactness (right). Error bars show 95% confidence intervals and solid line indicates a significant (P < 0.05) relationship between variables.

[13] NSW Government Office of Environment and Heritage. n.d. *Thylogale stigmatica*. Available from: https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10805

KANGAROO ISLAND DUNNART (*Sminthopsis aitkeni*)

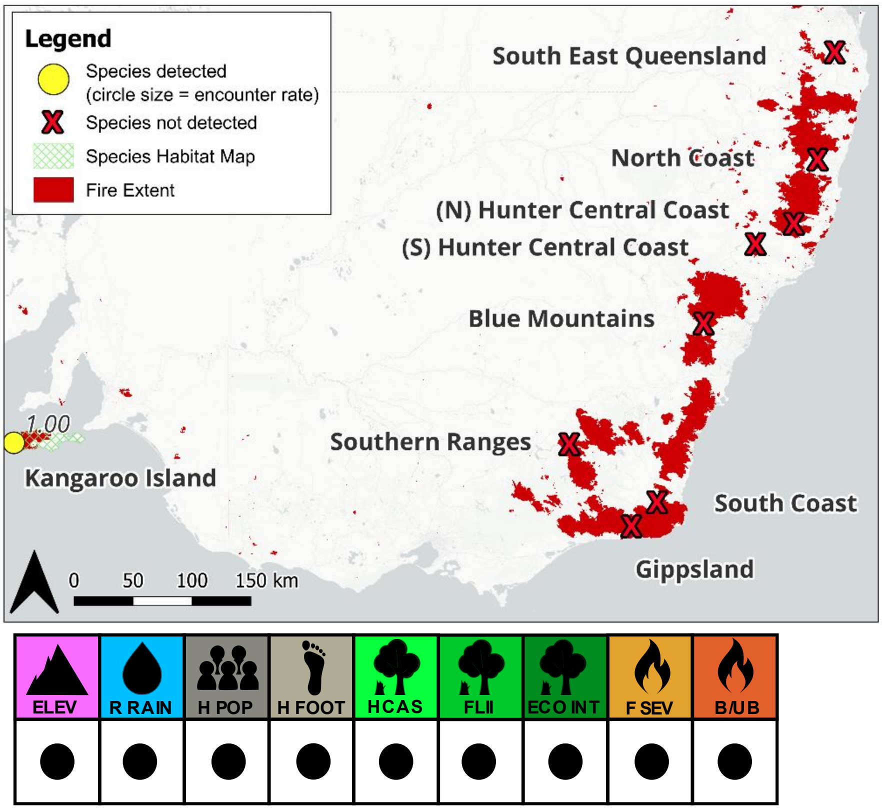


Figure 3.17. Map of Kangaroo Island dunnart encounter rate overlaid with fire extent and dunnart habitat range (top). Top models predicting the effects of different variables on dunnart occupancy (bottom).

Kangaroo Island dunnarts are found only on Kangaroo Island, South Australia, and were listed as Critically Endangered under the EPBC Act prior to the 2019/20 fires. Approximately 98% of their habitat was burnt, the highest proportion of any mammal assessed[6], with most areas experiencing high or extreme fire severity. Kangaroo Island dunnarts may experience high mortality during intense fires, and the lack of ground cover post-fire could leave them susceptible to predation by feral cats (*Felis catus*)[5].

KEY FINDINGS

- Kangaroo Island dunnarts were only encountered on Kangaroo Island, where their only known population exists (**Figure 3.17Figure**).
- Occupancy rates for the Kangaroo Island dunnart indicated relative stability through time (**Figure 3.18Figure**).
- All variables were found to be potentially important factors driving occupancy (**Figure 3.17**), although dunnart occupancy was not significantly affected by any of these variables (**Figure 3.18**).

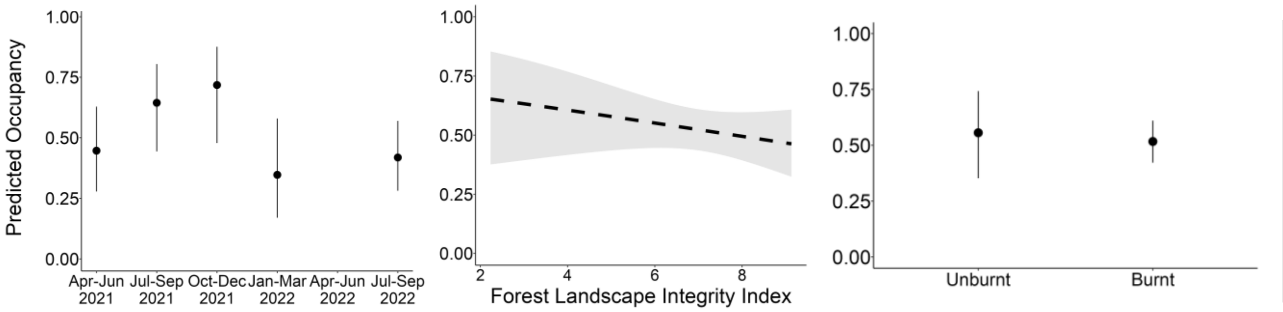


Figure 3.18. Kangaroo Island dunnart occupancy over time (left), with increasing forest landscape integrity (middle), and between burnt and unburnt habitats (right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

OTHER PRIORITY SPECIES

These two priority species, **Albert's lyrebird** and the **long-footed potoroo**, were detected during Eyes on Recovery surveys, however they were only recorded at one landscape and had too few data points to run detailed analyses. They are included below due to their listing on the Australian federal government's list of animals requiring urgent monitoring and management intervention following the 2019-20 bushfires and because of their importance for Eyes on Recovery partners.

Albert's lyrebird (*Menura alberti)*

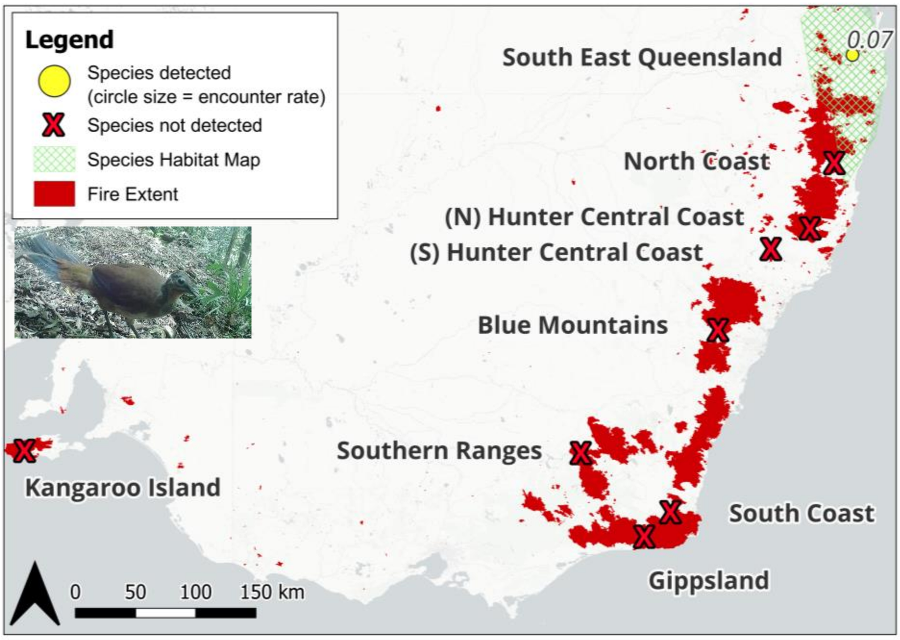


Figure 3.19. Map of Albert's lyrebird encounter rate overlaid with 2019-20 fire extent and lyrebird habitat range.

Albert's lyrebirds are listed as vulnerable in New South Wales and near threatened in Queensland, with around 3,500 breeding populations thought to exist in the wild[14]. Found only in a small area around the border of south-east Queensland and north-east NSW, they have one of the smallest distributions of any bird in Australia[14]. Albert's lyrebirds are threatened by land clearing and rainforest fragmentation and large-scale fires could potentially impact the entire population, especially individuals from outlying sub-populations[14].

KEY FINDINGS

Albert's lyrebirds were detected only in the South East Queensland landscape (**Figure 3.19**). In this landscape they were detected on 13 independent occasions.

Long-footed potoroo (*Potorous longipes*)

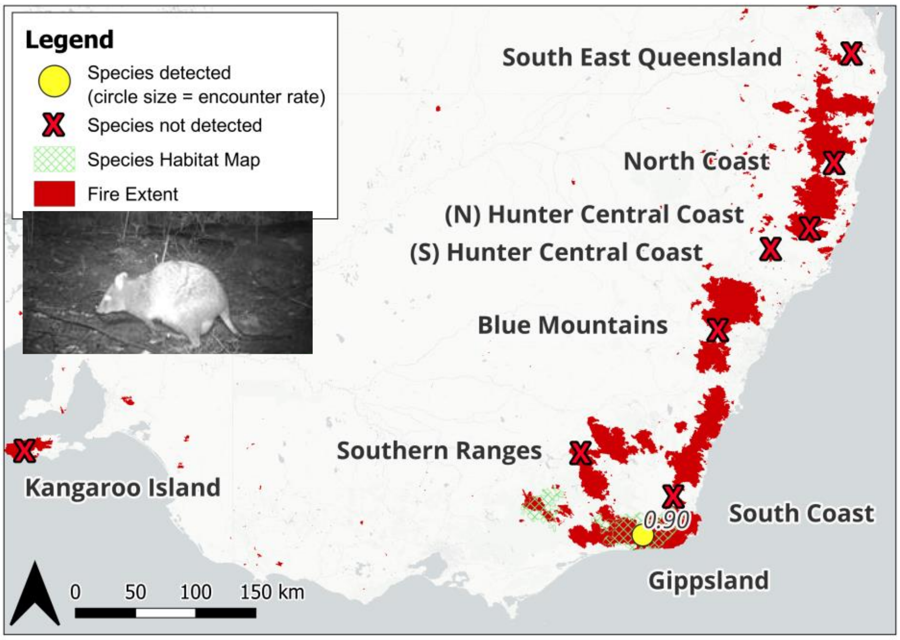


Figure 3.20. Map of long-footed potoroo encounter rate overlaid with 2019-20 fire extent and potoroo habitat range.

Long-footed potoroos are listed as Endangered under the EPBC Act and persist in three subpopulations in south-eastern NSW and eastern Victoria. Long-footed potoroos eat fungi, plants, and invertebrates and rely on dense forest understorey to shelter from predators[15], making them vulnerable following loss of cover due to fire. Approximately 82% of their habitat was burnt during the 2019/20 fire season, one of the highest proportions for all species assessed[6].

KEY FINDINGS

Long-footed potoroos were detected in only one Eyes of Recovery landscape, East Gippsland, even though one of the surveys in the South Coast NSW landscape was designed specifically to detect them (**Figure 3.20**). Further surveys are required to determine whether the NSW subpopulation is locally extinct or just persisting at very low densities.

[14] Australian Government Department of Climate Change, Energy, the Environment and Water, n.d., *Menura alberti* – Albert's Lyrebird. Available from: https://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=652
[15] Australian Government Department of Climate Change, Energy, the Environment and Water 2022. Conservation Advice for *Potorous longipes* (long-footed potoroo). Available from: https://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=217

INTRODUCED SPECIES

Introduced species are one of the top threats impacting listed threatened species in Australia[16]. Of the 12 introduced species detected across the Eyes on Recovery landscapes, 6 were encountered at high rates. These 6 species included introduced predators, namely the red fox (*Vulpes vulpes*) and feral cat (*Felis catus*), as well as introduced herbivores and other hooved mammals, including domestic cattle (*Bos taurus*), pigs (*Sus scrofa*), fallow deer (*Dama dama*) and rabbits (*Oryctolagus cuniculus*).

INTRODUCED PREDATORS

Since their introduction into Australia at the time of British colonisation, red foxes (*Vulpus vulpus*) and cats (*Felis catus*) have had huge impacts on Australian native species. Predation from cats and foxes is thought to be the main cause of extinction for at least 20 Australian animals and contributes to the ongoing declines of many more[17]. Scientists estimate around 88 million reptiles, 111 million birds and 367 million mammals are killed by foxes and cats in Australia each year[14].

Fire increases the impact of feral cats and foxes on native species as it temporarily removes the vegetation many species use for shelter, increasing their risk of mortality from predation. There is concern that cats and foxes may move into burnt areas following a fire to exploit this vulnerability[18]. Overall, the response of cats and foxes themselves to fire in Australia is context-specific, with any observed increases in activity generally occurring immediately following a fire[19].

KEY FINDINGS

- Both red foxes and cats were encountered most frequently in central and southern NSW, although foxes were encountered more in the Blue Mountains and South Coast NSW, while cats were encountered on Kangaroo Island where foxes were absent (**Figure 4.1, 4.2**).
- Red fox and feral cat occupancy did not show significant changes through time (**Figure 4.1, 4.2**).
- The most important factors predicting occupancy for red foxes were forest landscape integrity and both fire variables, although none of these variables had significant effects on their occupancy (**Figure 4.1**). The most important variables predicting cat occupancy were forest landscape integrity and recent rainfall. Again, none of these variables had a significant effect (**Figure 4.2**). For cats, fire variables were more important than the null model, however no significant effects were discovered.

[16] Ward et al. 2021 A national-scale dataset for threats impacting Australia's imperiled flora and fauna. Ecology and Evolution 11: 11749-11761.
[17] Stobo-Wilson et al. 2021 Counting the bodies: estimating the numbers and spatial variation of Australian reptiles, birds and mammals killed by two invasive mesopredators. Diversity and Distributions 28: 976-991.
[18] McGregor et al. 2016 Extraterritorial hunting expeditions to intense fire scars by feral cats. Nature Scientific Reports 6:22559.
[19] Doherty et al. 2023, Cats, foxes and fire: quantitative review reveals that invasive predator activity is most likely to increase shortly after fire. Fire Ecology 19 (22)

Red fox (*Vulpes vulpes*)

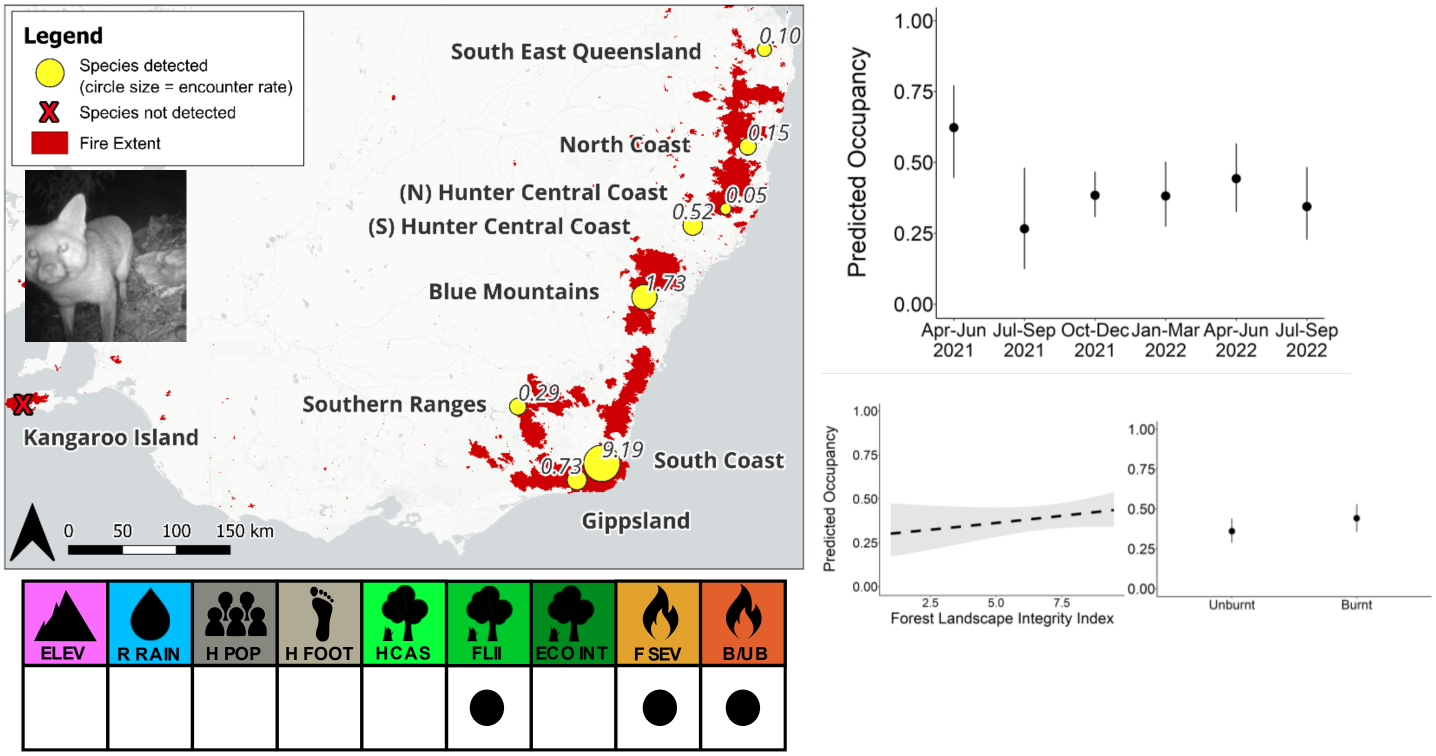


Figure 4.1. Map of red fox encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on fox occupancy (bottom left). Fox occupancy over time (top right), with increasing forest landscape integrity (bottom middle), and between different fire categories (bottom right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

Feral cat (*Felis catus*)

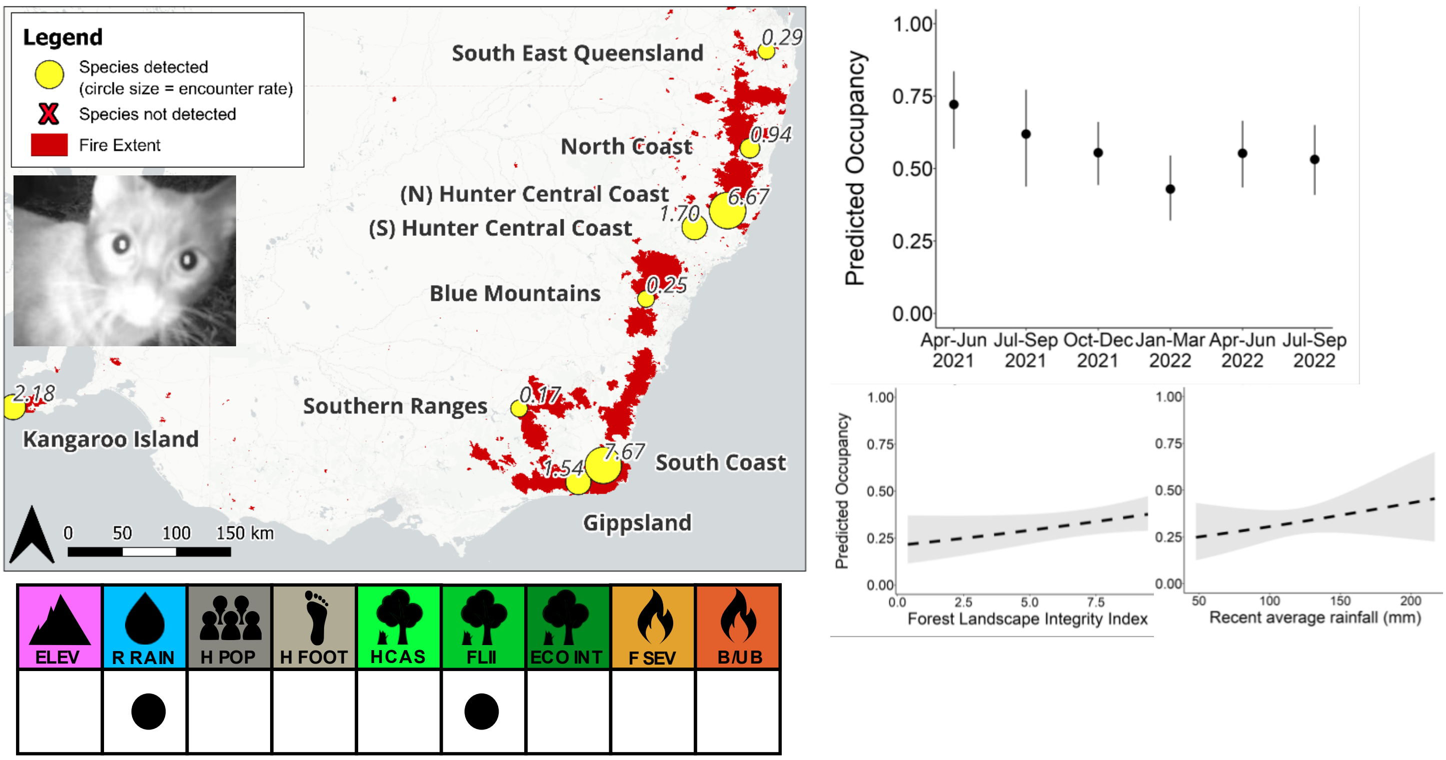


Figure 4.2. Map of feral cat encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on cat occupancy (bottom left). Cat occupancy over time (top right), with increasing forest landscape integrity (bottom middle), and recent average rainfall (bottom right). Error bars show 95% confidence intervals and dotted line indicates a non-significant relationship between variables.

INTRODUCED HOOVED MAMMALS AND OTHER HERBIVORES

Introduced hooved mammals and other introduced herbivores impact directly on Australian native species by degradation of shared ecosystems, competition and disease transfer. Rabbits (*Oryctolagus cuniculus*) are cited as impacting the largest number of threatened species in Australia, and feral pigs (*Sus scrofa*) threatening more than 100 species[20]. Feral herbivores impact native animals by grazing vegetation that animals use for food or shelter. Over-grazing of vegetation and trampling of the ground by ungulates causes soil erosion, leading to poor water quality in nearby streams and billabongs. Feral pigs (*Sus scrofa*) are omnivores. In addition to trampling the ground with their hooves, they cause further destruction by digging down for roots and tubers and preying on native bird and reptile eggs.

KEY FINDINGS

- Feral pigs were encountered in 8 landscapes (**Figure 4.3**), and European rabbits in 5 landscapes (**Figure 4.4**) Feral pigs were encountered most frequently in both Hunter Central Coast landscapes, and European rabbits were encountered most frequently in the South Coast landscape (**Figure 4.3, 4.4**).
- Feral pig occupancy was not able to be calculated through time due to insufficient data in some time periods (**Figure 4.3**). There were no significant trends in occupancy rates through time for European rabbits (**Figure 4.4**).
- Forest landscape integrity, HCAS, average recent rainfall and human population were all considered more important variables for feral pig occupancy, but their effects were not significant (**Figure 4.3**). Ecoregion intactness was the most important variable predicting European rabbit occupancy, with rabbit occupancy decreasing with higher ecoregion intactness (**Figure 4.4).** Both fire variables were considered more important than the null model for pigs and rabbits, but these variables did not show any significant relationships with occupancy (**Figure 4.3, 4.4**).

[20] Kearney et al. 2018 The threats to Australia's imperilled species and implications for a national conservation response. Pacific Conservation Biology 25(3):231–244

Feral pig (*Sus scrofa*)

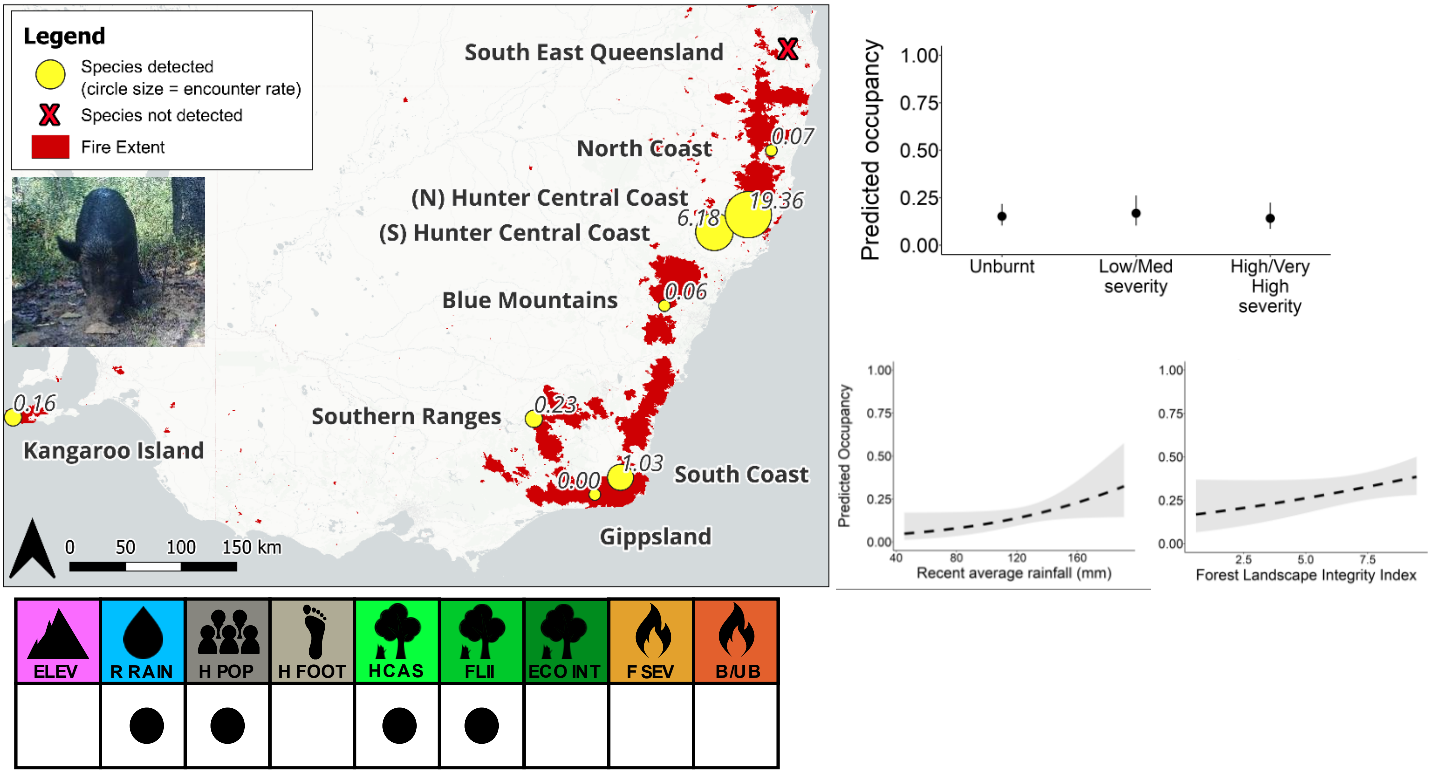


Figure 4.3. Map of feral pig encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on pig occupancy (bottom left). Pig occupancy across fire severity categories (top right), with increasing recent average rainfall (bottom middle), and forest landscape integrity (bottom right). Error bars show 95% confidence intervals, and dotted line indicates a non-significant relationship between variables.

European rabbit (*Oryctolagus cuniculus*)

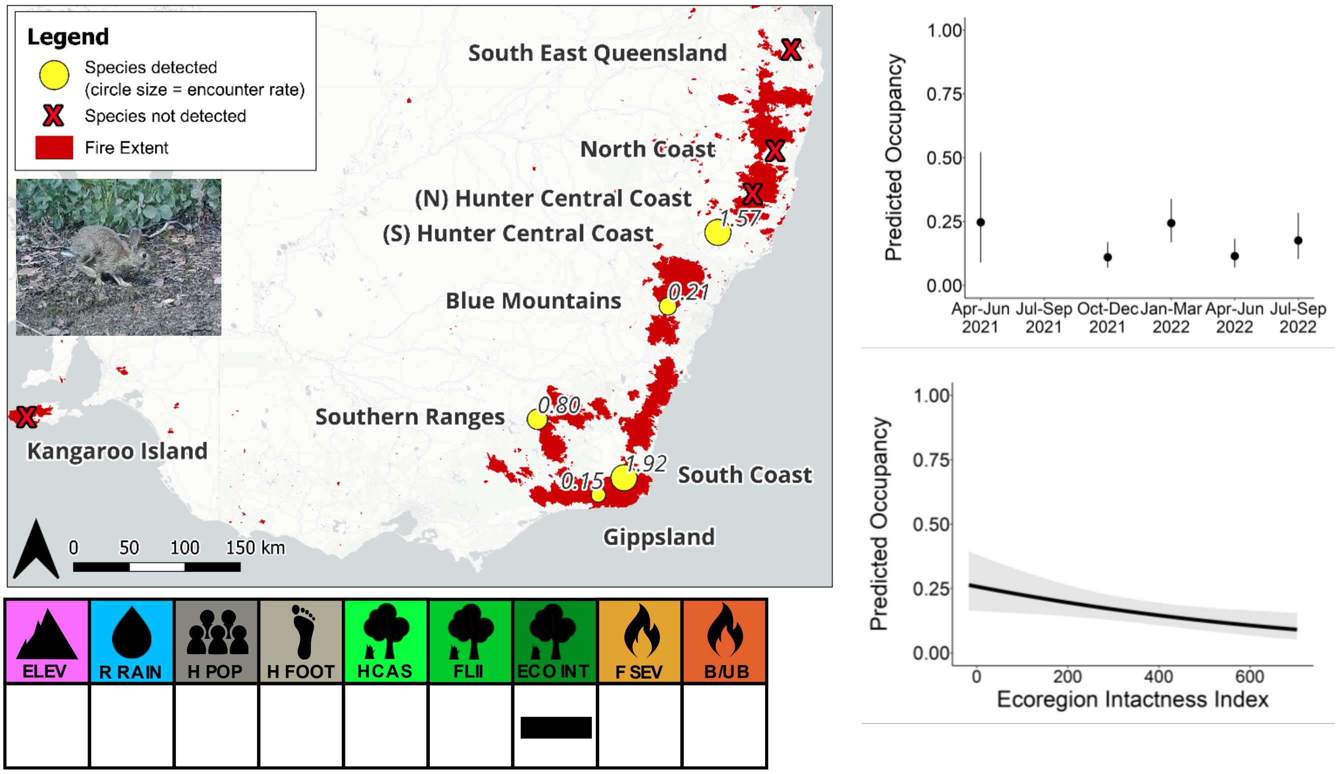


Figure 4.4. Map of European rabbit encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on rabbit occupancy (bottom left). Rabbit occupancy over time (top right), and with increasing ecoregion intactness (bottom right). Error bars show 95% confidence intervals, solid line indicates a significant ($P < 0.05$) relationship between variables, and dotted line indicates a non-significant relationship.

COMMON NATIVE SPECIES

The following 11 species or species groups are considered relatively ‘common’ native species, as they were generally detected at high rates across most landscapes and were not recognised as threatened or priority species. In some cases, however, species and species groups listed here were still of high interest for examination by on-ground Eyes on Recovery partners, as they were potentially felt to be highly vulnerable to the impacts of fire (e.g. the small mammals grouping that comprises rats, mice, antechinus and dasyurids weighing under 500g). As some of these species comprise the largest amount of data collected, there is more power to examine their overall trends in fire-affected landscapes.

MACROPODS (KANGAROOS, WALLABIES AND PADEMELONS)

Kangaroos, wallabies and pademelons are marsupials that belong to a group of animals native only to Australia and Papua New Guinea called macropods (meaning ‘big foot’). They are threatened by habitat clearing, competition with livestock and predation by introduced species like red foxes (*Vulpes vulpes*). Changes in bushfire patterns can also impact macropod habitat and may have negative impacts on some species that preferred more vegetatively complex habitat types but could also provide some benefits to species that prefer more open habitat. Over the past two centuries, New South Wales has seen a decline in macropod species, with smaller and more specialised species most negatively affected.

KEY FINDINGS

- Of all the macropod species examined, red-necked pademelons were encountered in the lowest number of landscapes (4 landscapes), with eastern grey kangaroos found in 6 landscapes and red-necked wallabies and swamp wallabies found in every landscape except Kangaroo Island (8 landscapes) (**Figure 5.1, 5.2, 5.3, 5.4**). Eastern grey kangaroos were encountered at the greatest rates in mid to southern NSW landscapes, and especially in the Southern Ranges and Blue Mountains landscapes (**Figure 5.1**). Red-necked wallabies and swamp wallabies were encountered at greatest rates in the South Hunter Central Coast landscape (**Figure 5.2, 5.3**) and red-necked pademelons were encountered most frequently in both Hunter Central Coast landscapes (**Figure 5.4**).
- Eastern grey kangaroos displayed variation in occupancy rates through over time, with occupancy in Oct-Dec 2021 significantly lower than Apr-Jun 2021, Jan-Mar 2022 and Apr-Jun 2022 (**Figure 5.1**). Red-necked wallaby occupancy showed a similar pattern, with the lowest occupancy rate in Oct-Dec 2021, and significantly higher occupancy rates in the following time periods (**Figure 5.2**). Swamp wallaby occupancy was also lower in Oct 2021 and until March 2022 (warmer months), compared with earlier and later cooler periods (**Figure 5.3**). Red-necked pademelon occupancy could not be estimated through time.
- Fire variables were not identified as important variables influencing macropod occupancy, although they were always considered more important than the null model. For eastern grey kangaroos, occupancy increased with higher average recent rainfall (**Figure 5.1**). For both red-necked wallabies and swamp wallabies, occupancy decreased at higher elevations (**Figure 5.2, 5.3**). For red-necked pademelons all variables except fire severity were considered equally important in predicting occupancy, although there were no significant relationships between these variables and pademelon occupancy (**Figure 5.4**).

Eastern grey kangaroo (*Macropus giganteus)*

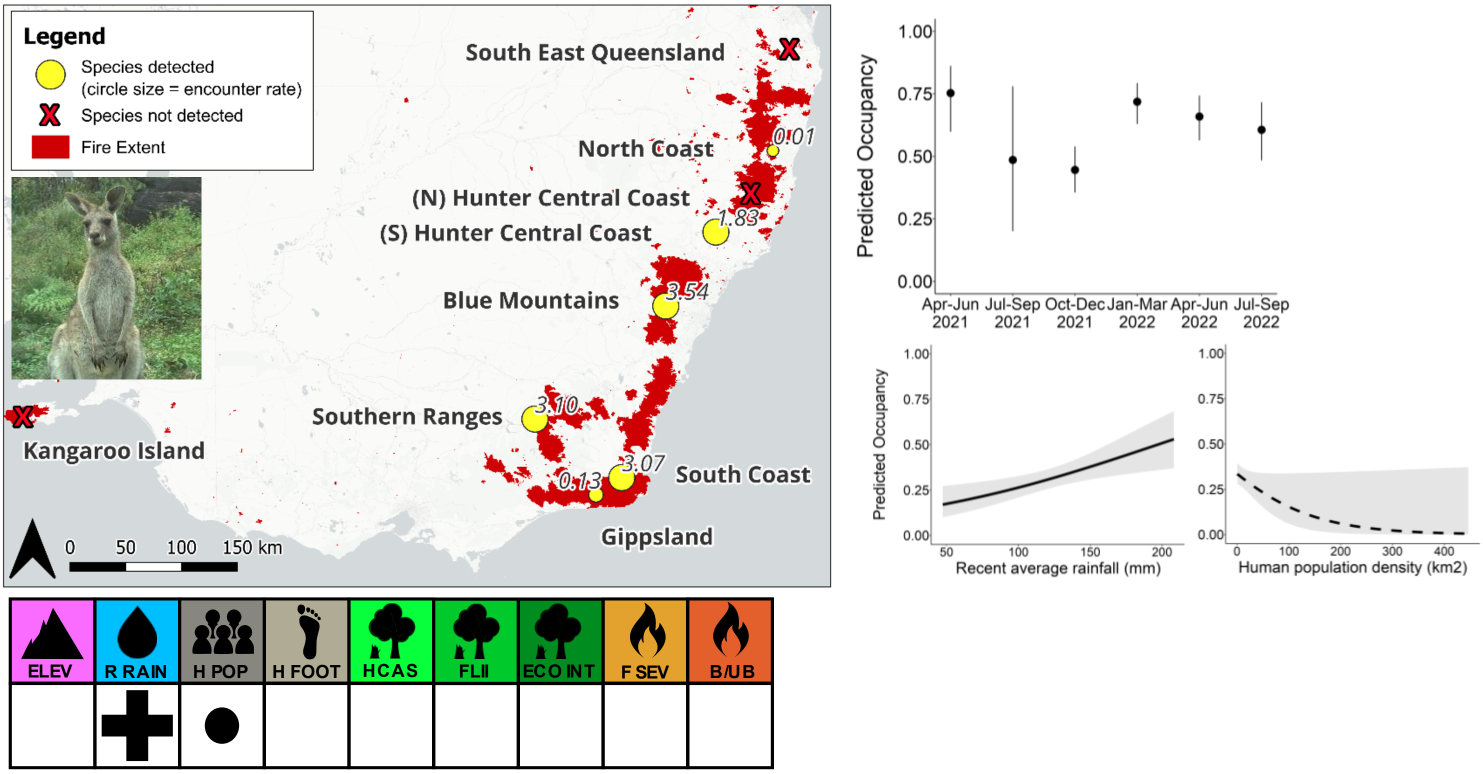


Figure 5.1. Map of eastern grey kangaroo encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables kangaroo occupancy (bottom left). Kangaroo occupancy over time (top right), with increasing recent average rainfall (bottom middle), and human population (bottom right). Error bars show 95% confidence intervals, solid line indicates a significant (P < 0.05) relationship between variables, and dotted line indicates a non-significant relationship.

Red-necked wallaby (*Notamacropus rufogriseus)*

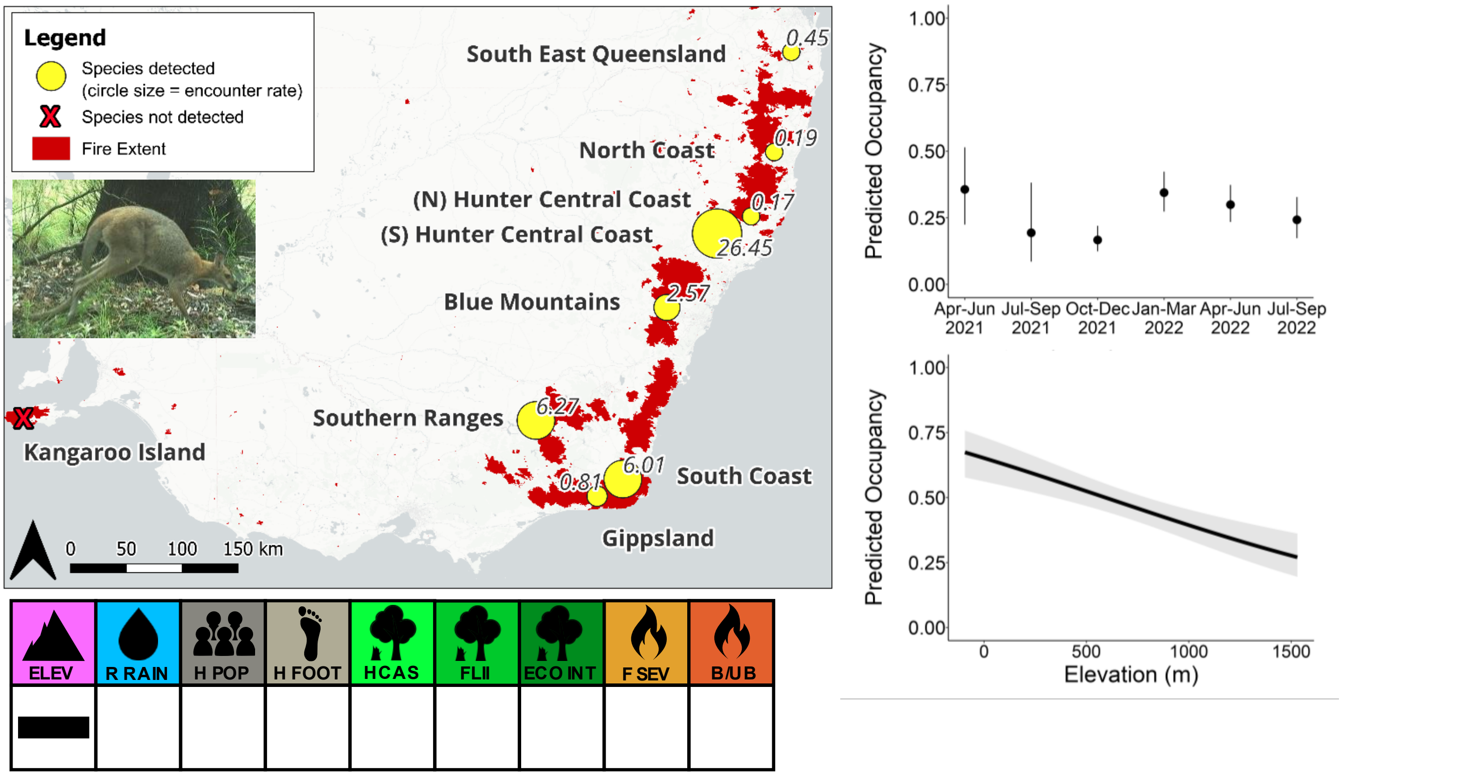


Figure 5.2. Map of red-necked wallaby encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on red-necked wallaby occupancy (bottom left). Red-necked wallaby occupancy over time (top right), and with increasing elevation (bottom right). Error bars show 95% confidence intervals, solid line indicates a significant (P < 0.05) relationship between variables.

Swamp wallaby (*Wallabia bicolor)*

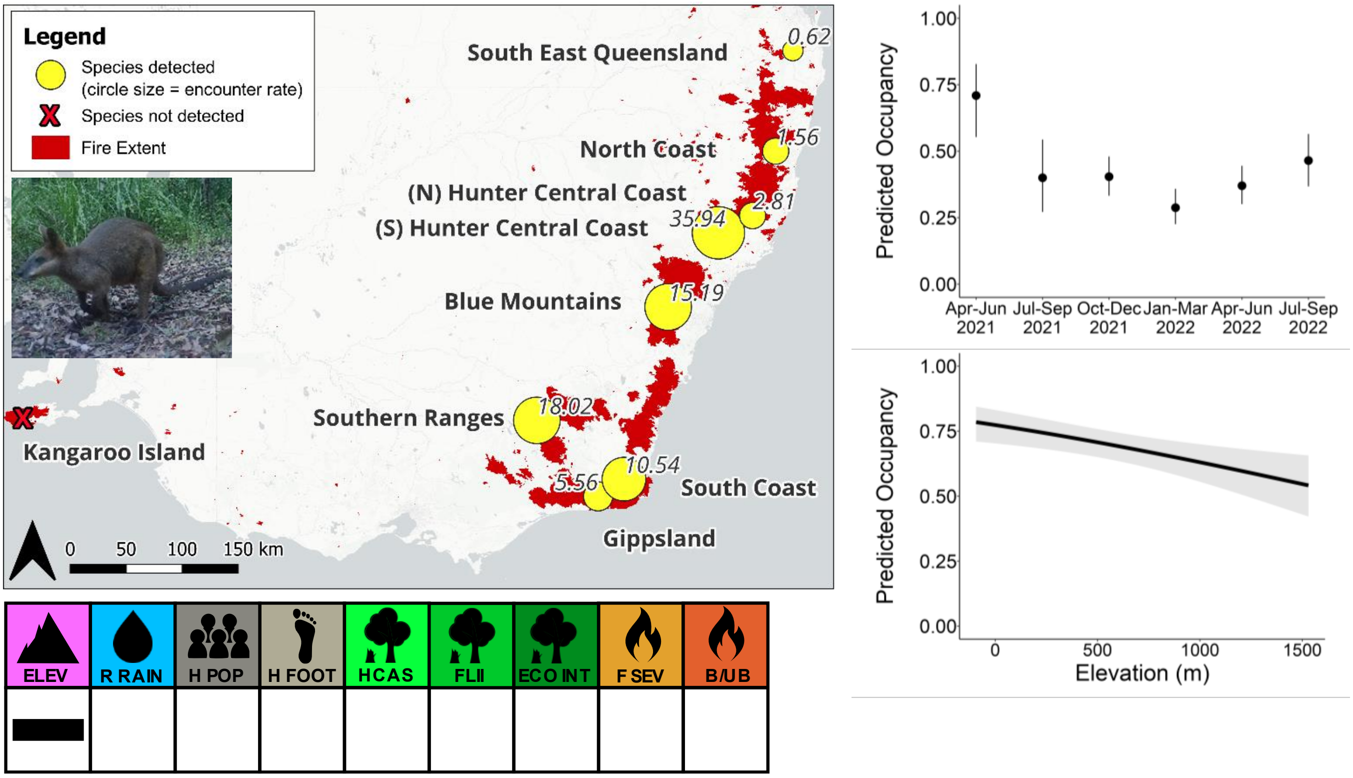


Figure 5.3. Map of swamp wallaby encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on swamp wallaby occupancy (bottom left). Swamp wallaby occupancy over time (top right), and with increasing elevation (bottom right). Error bars show 95% confidence intervals, solid line indicates a significant (P < 0.05) relationship between variables.

Red-necked pademelon (*Thylogale thetis)*

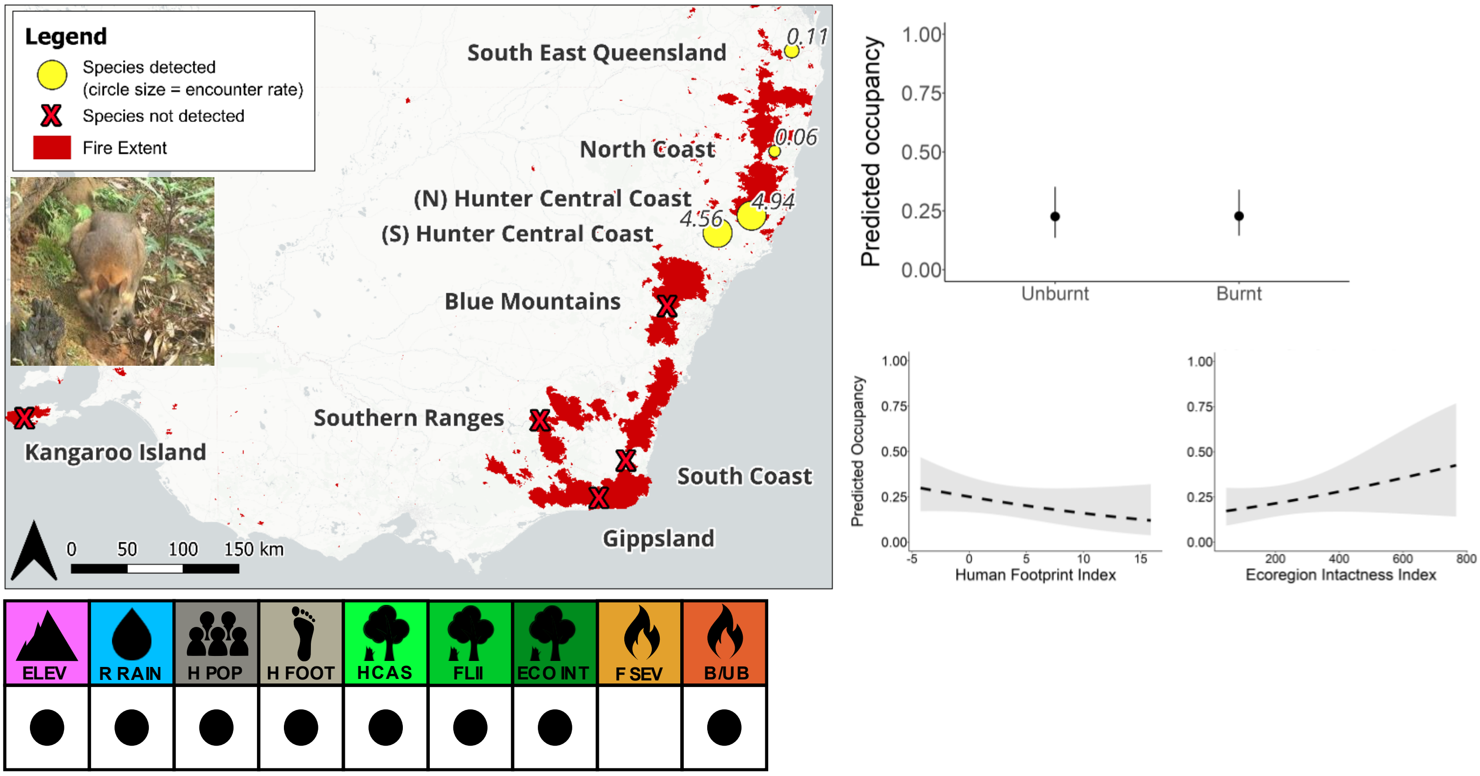


Figure 5.4. Map of red-necked pademelon encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on red-necked pademelon occupancy (bottom left). Red-necked pademelon occupancy across burnt and unburnt habitat (top right), with increasing human footprint (bottom middle), and ecoregion intactness (bottom right). Error bars show 95% confidence intervals. The dotted lines indicate non-significant relationships.

COMMON BANDICOOT SPECIES

Since European settlement, bandicoots have undergone several species extinctions and significant range contractions largely due to land clearing and the introduction of predators like red foxes (*Vulpes vulpes*) and cats (*Felis catus*)[21]. Of the 12 known species of bandicoot in Australia, approximately half are now extinct, or are threatened with extinction[21]. Long-nosed bandicoots (*Perameles nasuta*) and northern brown bandicoots (*Isoodon macrourus*) are two more commonly encountered bandicoot species, which are located in coastal and sub-coastal areas across northern and eastern Australia. The long-nosed bandicoot is found in eastern Australia, from Queensland, New South Wales and Victoria[22]. The northern brown bandicoot is found across northern and eastern Australia and in south eastern New Guinea[23]. The relationship between fire and bandicoot species, including the long-nosed bandicoot and northern brown bandicoot, is complex. In some systems, fire regimes may be the most important determinant of bandicoot survival, with fire often correlating to declines in survival rates over time[24]. Bandicoots may also prefer unburnt habitat for particular types of vegetation to forage and build nests[25].

KEY FINDINGS

- Long-nosed bandicoots were encountered in the most landscapes (8 landscapes), with highest encounter rates occurring in the Hunter Central Coast NSW landscapes (**Figure 5.5**). Northern brown bandicoots were encountered at greatest rates in the North Hunter Central Coast NSW landscape and were only encountered in the northern Eyes on Recovery landscapes that fell within their predicted range (**Figure 5.6**).
- Long-nosed bandicoots showed some variation in occupancy over time, with their occupancy generally higher in Jan-Mar 2022 and Jul-Sep 2022 than other periods (**Figure 5.5**). Northern brown bandicoot occupancy was generally similar across periods, although it was higher in the Oct-Sep 2021 period (**Figure 5.6**).
- Fire variables were identified as important to long-nosed bandicoot occupancy but did not appear to significantly influence occupancy (**Figure 5.5**). Average recent rainfall had a significant negative relationship with northern brown bandicoot occupancy, while fire variables were not among the most important variables (**Figure 5.6**).

[21] NSW Government Department of Environment and Heritage. 2023. Bandicoots. Available from: https://www.environment.nsw.gov.au/topics/animals-and-plants/native-animals/native-animal-facts/bandicoots
[22] Australian Museum. 2022. Long-nosed bandicoot. Available from: https://australian.museum/learn/animals/mammals/long-nosed-bandicoot/
[23] Australian Museum. 2024. Northern Brown Bandicoot. Available from: https://australian.museum/learn/animals/mammals/northern-brown-bandicoot/
[24] Pardon, G. L. et al. 2003. Determinants of Survival for the Northern Brown Bandicoot under a Landscape-Scale Fire Experiment. *Journal of Animal Ecology* **72**: 106–115.
[25] Macgregor, C. I. et al. 2022. The effects of fire on the Southern Long-nosed Bandicoot (Perameles nasuta Geoffroy) in a highly heterogeneous landscape. Thesis.

Long-nosed bandicoot (*Perameles nasuta)*

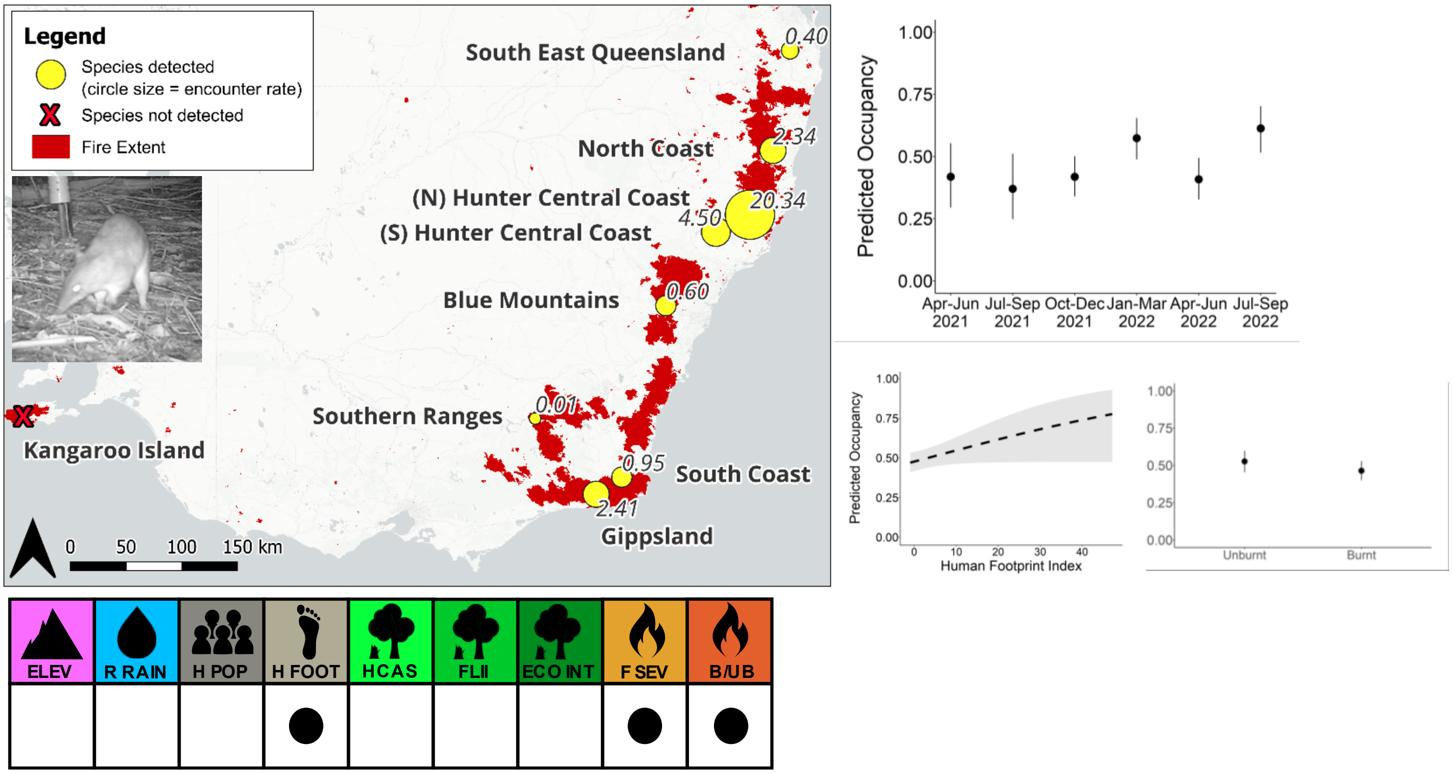


Figure 5.5. Map of long-nosed bandicoot encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on long-nosed bandicoot occupancy (bottom left). Long-nosed bandicoot occupancy over time (top right), with increasing human footprint index (bottom middle), and between burnt and unburnt sites (bottom right). Error bars show 95% confidence intervals. The dotted line indicates a non-significant relationship.

Northern brown bandicoot (*Isoodon macrourus)*

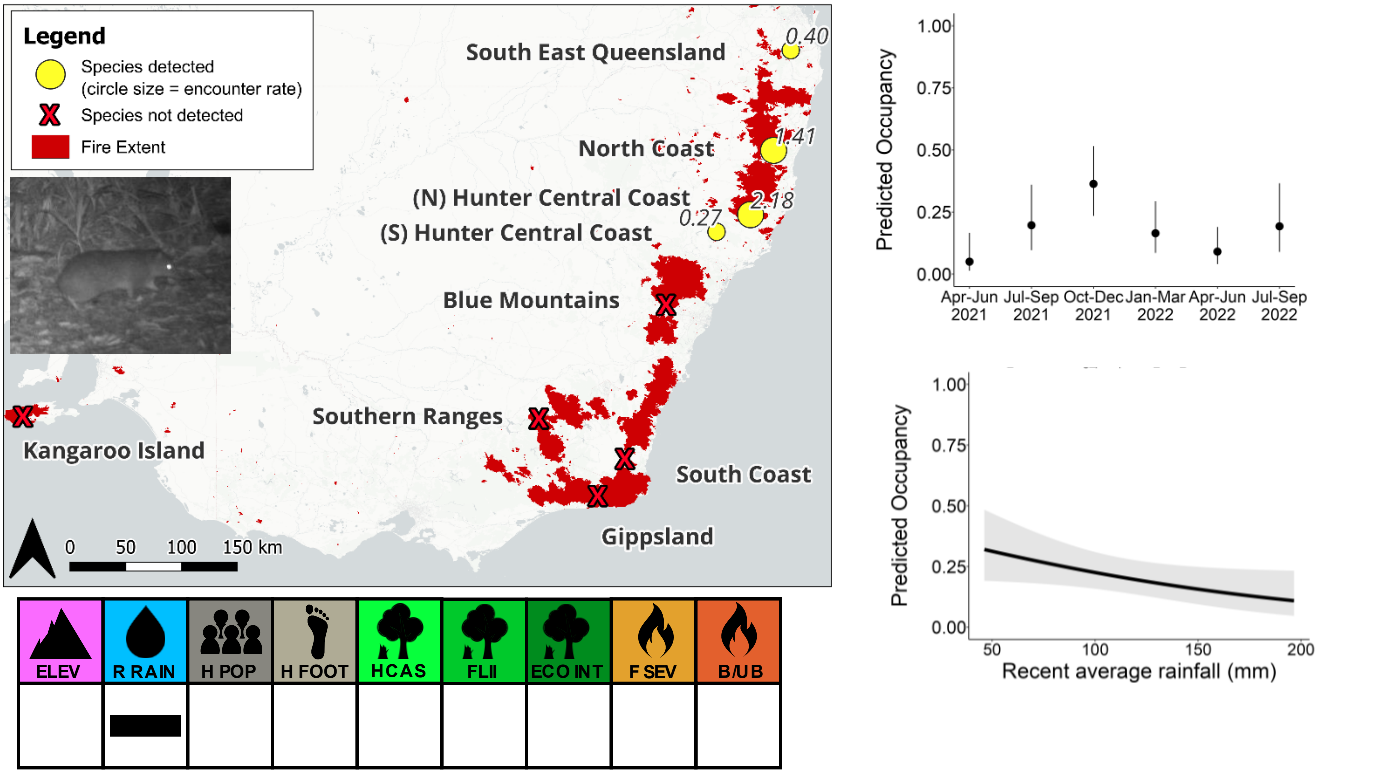


Figure 5.6. Map of northern brown bandicoot encounter rate overlaid with 2019-20 fire extent (top left). Top models predicting the effects of different variables on northern brown bandicoot occupancy (bottom left). Northern brown bandicoot occupancy over time (top right), and with increasing recent average rainfall (bottom right). Error bars show 95% confidence intervals, solid line indicates a significant ($P < 0.05$) relationship between variables.

OTHER MAMMALS

It was estimated that approximately 143 million mammals were killed or displaced by the 2019-20 Australian bushfires[26]. While the impacts of these fires were enormous, many Australian native mammals have developed characteristics and behaviours that help them survive fire and occupy burnt landscapes in heavily fire-impacted environments where vegetation is much reduced, and food and shelter is limited. For example, burrowing species, like wombats (*Vombatus sp.*) will escape underground to evade fire, with their burrows also providing safe refuge underground for many other non-burrowing wildlife from echidnas (*Tachyglossidae sp*.) to small mammals like hopping mice (*Notomys sp.*), skinks (Family: Scincidae) and invertebrates[27]. Possums and other arboreal animals may move higher up into trees and use hollows to escape from lower intensity fires[28]. In the wake of bushfire, short-beaked echidnas and small marsupials like brown and yellow-footed antechinus may use torpor, lowering their body temperature and limiting their activity to suppress their energy use and therefore the need to seek food[29,30]. In post-fire environments, however, many native mammals are also at risk of increased predation, as reduced vegetation complexity limits shelter opportunities. For example, native rodent species (the pale field rat, *Rattus tunneyi*, and the western chestnut mouse, *Pseudomys nanus*) abundance was lower in areas impacted by intense fire compared to unburned areas, mostly due to predation by feral cats rather than direct mortality due to the fire itself[31].

KEY FINDINGS

- Short-beaked echidna, small mammals (<500g) and possum species were encountered in all landscapes (9 landscapes), while wombats were detected only in 6 landscapes (**Figure 5.7, 5.8, 5.9, 5.10**). The highest encounter rates for common wombats occurred in the Southern ranges, South Coast and South Central Hunter Coast landscapes (**Figure 5.**7). Echidnas were encountered most frequently in the South Hunter Central Coast NSW and Kangaroo Island landscapes (where an endemic subspecies *Tachyglossus aculeatus multiaculeatus* is found; **Figure 5.8**) while the highest encounter rates for small mammals was in the Kangaroo Island landscape (**Figure 5.9**) and the highest encounter rates for possum species occurred in the north Hunter Central Coast landscape (**Figure 5.10**).
- Small mammals showed similar occupancy over time (**Figure 5.9**), while occupancy was generally higher for common wombats in Jan-Mar 2022 than in other periods (**Figure 5.7**), for short-beaked echidnas in both Jul-Sep 2021 and Apr-Jun 2022 (**Figure 5.8**), and for possums in Jul-Sep 2021 (**Figure 5.9**).
- Fire variables were not identified as important variables influencing occupancy of these species, although they were more important than the null models. Common wombat occupancy increased with higher average recent rainfall (**Figure 5.7**), while echidna occupancy was higher with increasing forest landscape integrity (**Figure 5.8**). Both small mammal (<500g) and possum occupancy increased with greater ecoregion intactness, and possum occupancy also increased with higher human footprint (**Figure 5.9, 5.10**).

[26] Van Eeden, L. et al. 2020. Impacts of the unprecedented 2019–2020 Bushfires on Australian animals. Report Prepared for WWF-Australia.
[27] Thornett et al. 2015. Interspecies co-use of southern hairy-nosed wombat (*Lasiorhinus latifrons*) burrows. Australian Mammalogy 39: 205–212.
[28] Zylstra, P. 2022. Quantifying the direct fire threat to a critically endangered arboreal marsupial using biophysical, mechanistic modelling. Austral Ecology 48: 266–288.
[29] Nowack, J et al. 2016. Cool echidnas survey the fire. Proc. R. Soc. B.2832016038220160382
[30] Stawski, C. et al. 2015. The importance of mammalian torpor for survival in a post-fire landscape. Biol. Lett.112015013420150134
[31] Leahy, L. et al. 2015. Amplified predation after fire suppresses rodent populations in Australia's tropical savannas. Wildlife Research 42: 705.

Common wombat (*Vombatus ursinus)*

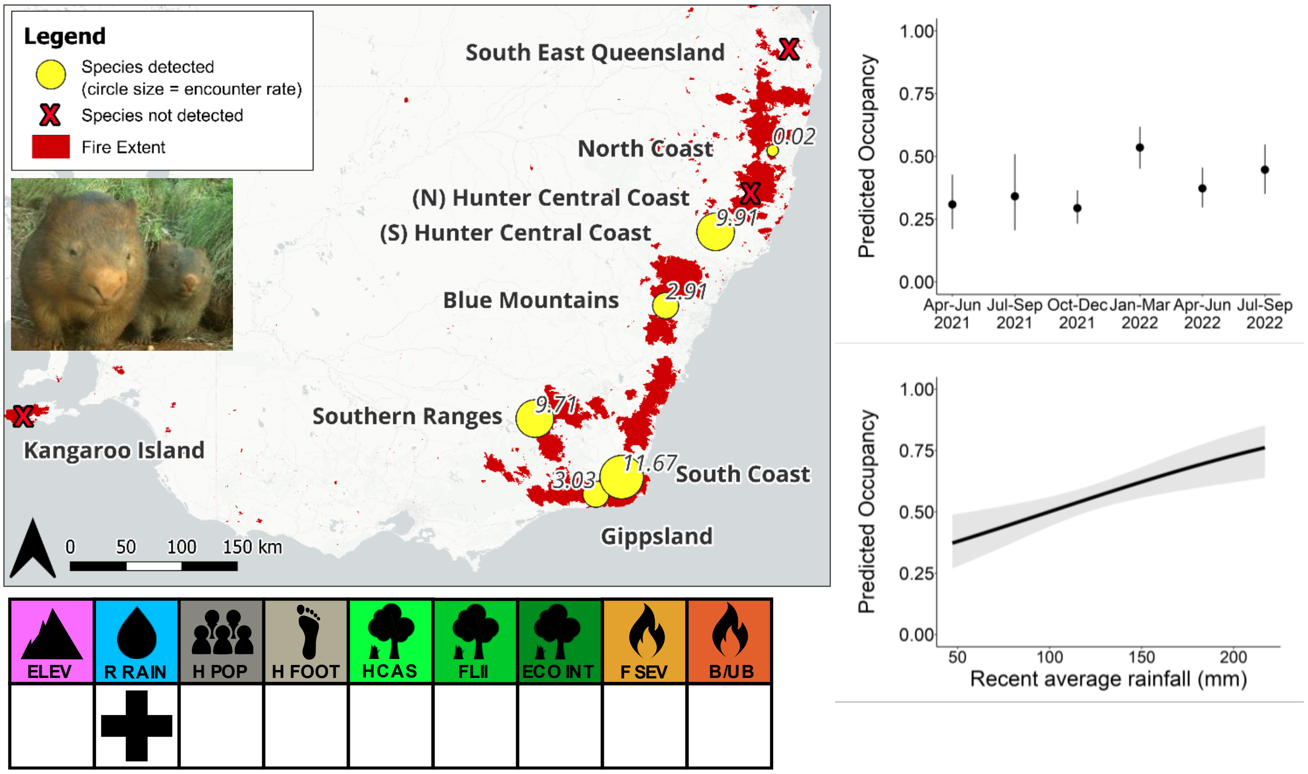


Figure 5.7. Map of common wombat encounter rate overlaid with fire extent (top left). Top models predicting the effects of different variables on common wombat occupancy (bottom left). Common wombat occupancy over time (top right), and with increasing recent average rainfall (bottom right). Error bars show 95% confidence intervals. The solid line indicates a significant ($P < 0.05$) relationship.

Short-beaked echidna (*Tachyglossus aculeatus)*

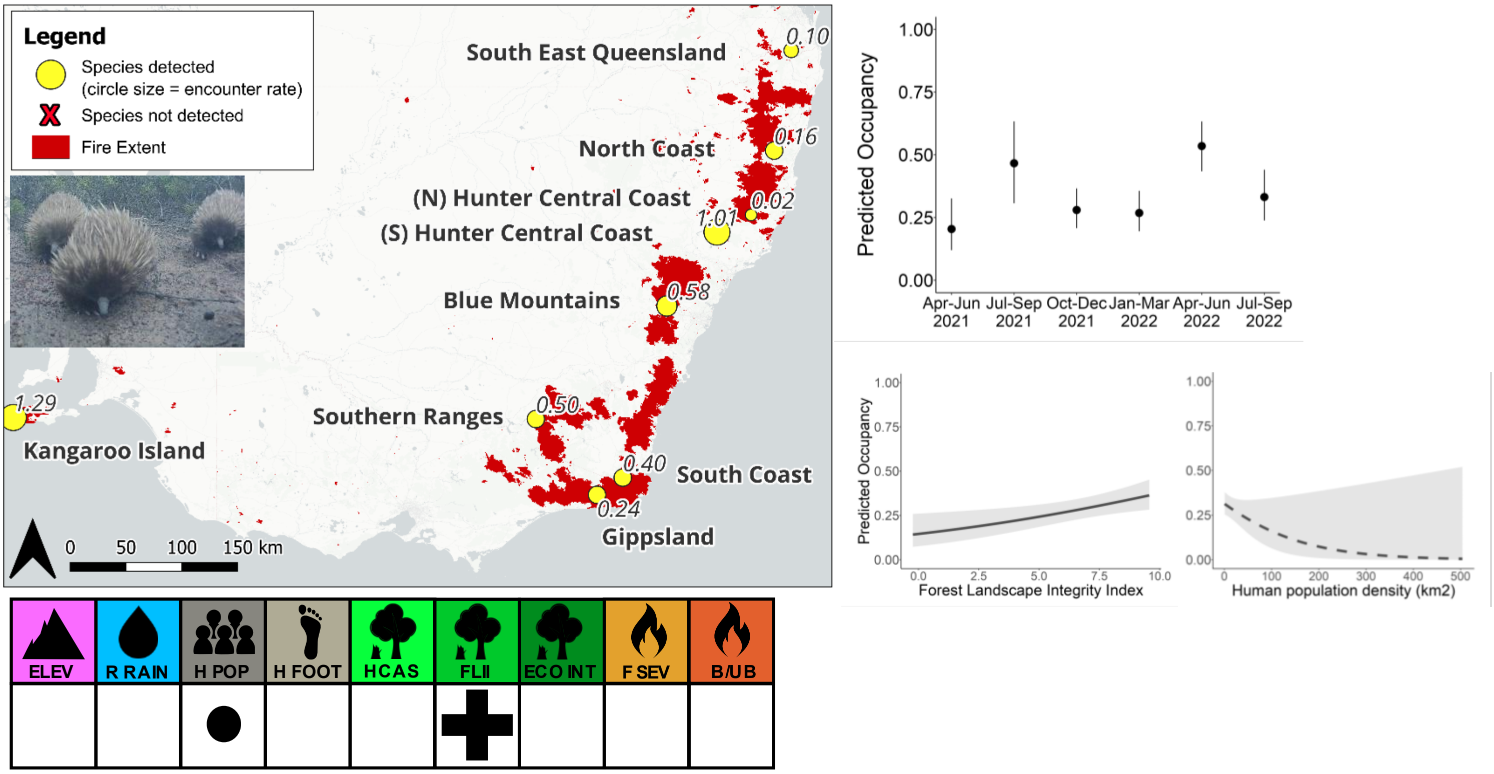


Figure 5.8. Map of short-beaked echidna encounter rate overlaid with 2019-20 fire extent (top left). Top models predicting the effects of different variables on echidna occupancy (bottom left). Echidna occupancy over time (top right), with an increasing forest landscape integrity index (bottom middle), and with increasing human population density (bottom right). Error bars show 95% confidence intervals. The solid line indicates a significant ($P < 0.05$) relationship, the dotted line indicates a non-significant relationship.

Small mammal species (<500g)

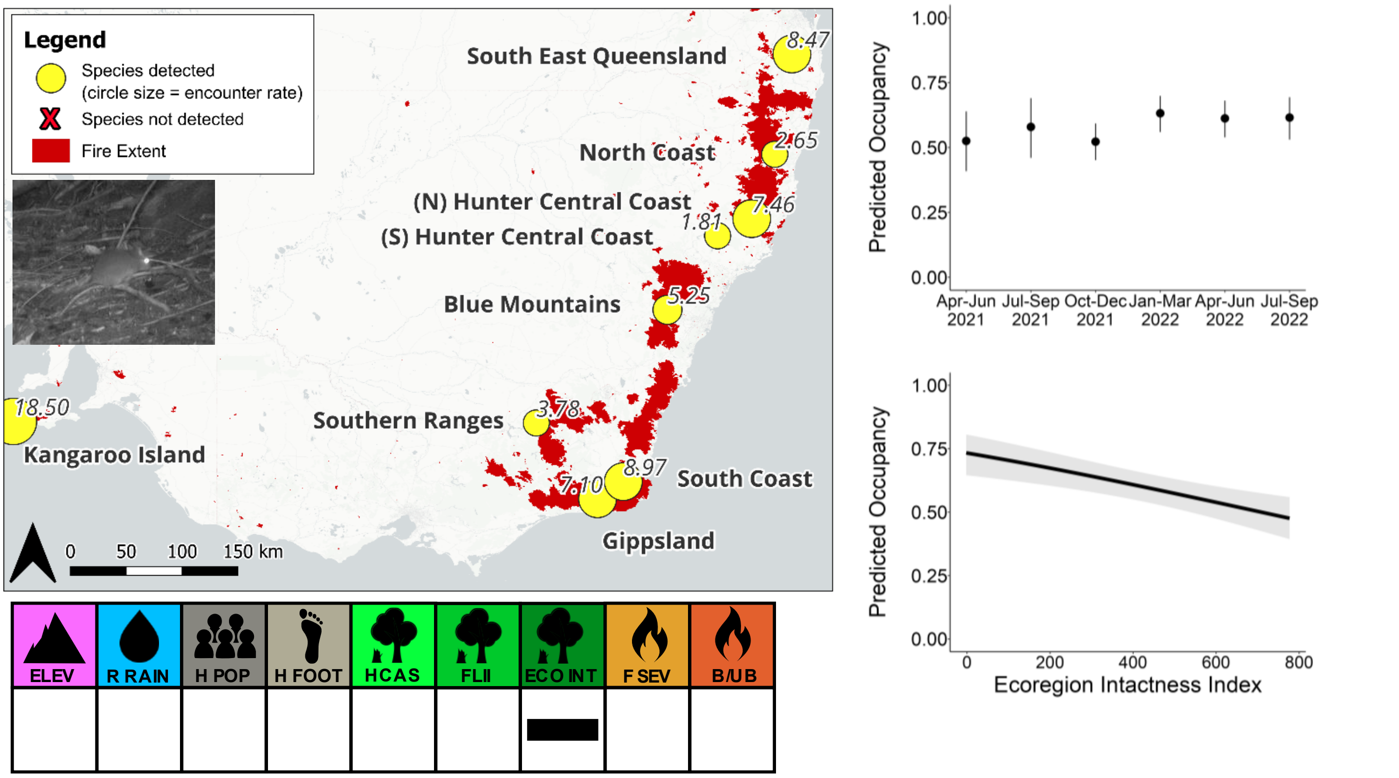


Figure 5.9. Map of small mammal (<500g) encounter rate overlaid with 2019-20 fire extent (top left). Top models predicting the effects of different variables on small mammal (<500g) occupancy (bottom left). Small mammal (<500g) occupancy over time (top right), and with increasing ecoregion intactness (bottom right). Error bars show 95% confidence intervals. The solid line indicates a significant (P < 0.05) relationship.

Possum species

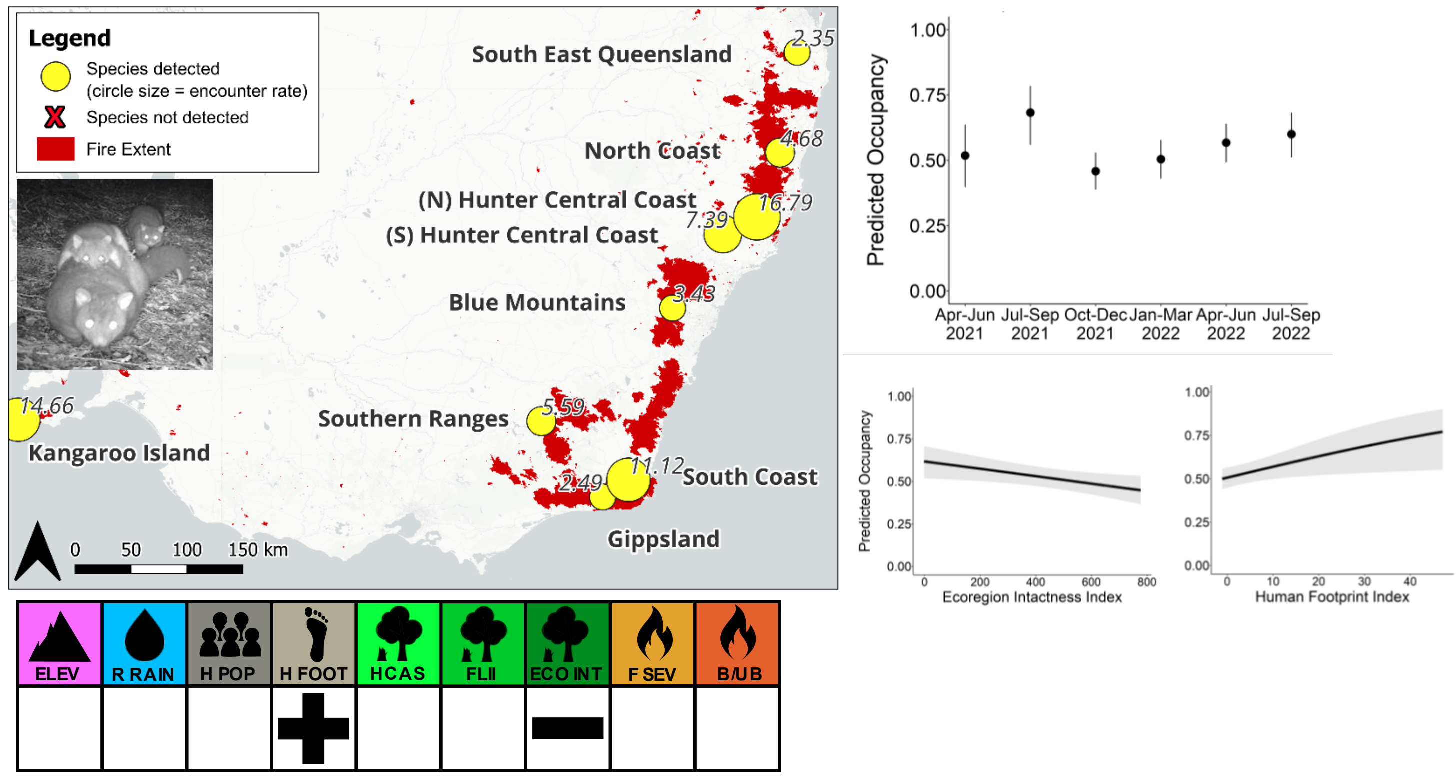


Figure 5.10. Map of possum (common ring-tailed possum, common brush-tailed possum, short-eared possum and mountain brush-tailed possum) encounter rate overlaid with 2019-20 fire extent (top left). Top models predicting the effects of different variables on possum occupancy (bottom left). Possum occupancy over time (top right), with increasing ecoregion intactness (bottom middle), and with increasing human footprint (bottom right). Error bars show 95% confidence intervals. The solid lines indicate significant (P < 0.05) relationships.