

Terrestrial mammal use of artificial Habitat Pods designed for burnt environments

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DECLARATION

I declare that this thesis, as a whole or in parts, has not been submitted for a higher degree to any other university or institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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- Associate Professor Melanie Bishop for her support throughout all statistical analyses.

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Emily/Hegarty

Date 24/09/2022

This thesis is formatted to meet the requirements of Macquarie University. This includes the requirement of an abstract of 200 words, 2cm margins, 1.5x line spacing, and Figures and Tables embedded within the text.

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Candidate's statement about the impact of COVID-19 changes on the thesis

Dear Examiner,

Many of our HDR candidates have had to make changes to their research due to the impact of COVID-19. Below you will find a statement from the candidate, approved by their Supervisory Panel, that indicates how their original research plan has been affected by COVID-19 restrictions. Relevant ongoing restrictions caused by COVID-19 will also be detailed by the candidate.

Candidate's Statement

The various logistical complexities of Covid resulted in most fieldwork being completed by myself, with the occasional assistance of one other person, and rarely in a team. This resulted in fieldwork taking a more significant proportion of time than initially expected and restricted the capacity for additional surveys. However, thankfully, the overall duration of this thesis period was extended by four months to partially accommodate interruptions such as these.

Abstracts

Australia's remaining ground-dwelling mammal species are increasingly threatened by the extensive loss of understory vegetation associated with intensifying fire regimes. We field-tested the potential for an artificial refuge structure (The Habitat Pod) to support these species (hereafter "Prey") within burnt environments. The impacts of Habitat Pods on fauna were assessed by implementing a BACI experimental design within a recently burnt area of the Hawkesbury River catchment, completed across 24 sites over 21 weeks. Animal interactions with the Habitat Pods, and the effects of Habitat Pods on microclimates were also assessed. My major finding was that prey readily interacted with Habitat Pods, which were likely perceived as sheltered runways, and that the design was suitable for deployment into burnt environments. I did not detect a significant influence of the Habitat Pods on overall fauna activity, but this was likely due to the low density of Pods distributed, and large inter-site variability. This project highlighted the challenges prey face within burnt environments, where I confirmed there was less understory, fewer natural refuges, and higher predator activity. This project highlighted the great potential for artificial refuges to support ground-dwelling prey within burnt environments. Future research could deploy a higher number of Habitat Pods and aim to deploy Pods much sooner after a burn. Further research should also address whether Habitat Pods directly increase prey survival, leading to higher population persistence in burnt areas.

Introduction

Earth is losing species to extinction at 1000 times the natural background rate (Pimm et al., 2014). This decline is driven by anthropogenic influences, such as altered climate regimes (Bradstock, 2010), extensive habitat degradation (Scanes, 2018), and invasive species (Doherty et al., 2015b). Increasingly, these threats compound, with devastating impacts on local ecosystems (Brook et al., 2008). These threats have been particularly impactful across Australia (Woinarski et al., 2011, Burbidge and McKenzie, 1989, Doherty et al., 2016), resulting in the continent having the highest mammal extinction rate in the world (Johnson, 2006).

Invasive predators such as feral cats (*Felis catus*) and the red fox (*Vulpes vulpes*) have had particularly severe impacts on Australian wildlife (Banks and Dickman, 2007, Courchamp et al., 2003, Salo et al., 2007). Cats and foxes are now found across 99.8% and 75% of the continent, respectively (Legge et al., 2017, Centre for Invasive Species Solutions, 2011). Animals within their preferred prey size, the so-called “Critical Weight Range” (~35g – 5.5kg; Burbidge and McKenzie, 1989) have shown the most significant declines of all Australian fauna (Chisholm and Taylor, 2010, Johnson and Isaac, 2009, Dickman and Newsome, 2015).

Ground-dwelling critical weight range mammals (hereafter “small mammals”) are particularly susceptible to the hunting strategies of cats and foxes (Johnson, 2006). Both predators are “surplus killers”, meaning that they kill available prey beyond any need for consumption (Mahon, 2009, Short et al., 2002). Individuals are known to continue hunting their personal preference of prey even when the species becomes scarce, ultimately leading to localised extinctions (Dickman and Newsome, 2015, Frank et al., 2014). Considering these circumstances, it is unsurprising that feral cats and foxes have been implicated in the extinction of at least 20 of these ground-dwelling small mammals (Dickman and Newsome, 2015, Frank et al., 2014, Green, 2002, Woinarski et al., 2015).

Native species’ capacity to cope with this increased predation pressure is likely reduced by widespread habitat degradation. Degraded habitat can decrease refuge availability for terrestrial prey species and increase predation pressure (Kutt and Woinarski, 2007, Legge et al., 2011). Reduced structural complexity benefits predators by facilitating prey detection

and pursuit (Lagos et al., 1995, Longland and Price, 1991, Warfe and Barmuta, 2004). Increased vulnerability to predation can leave prey species stressed (Johnstone et al., 2011), resulting in decreased foraging efficiency and potentially maladaptive avoidance behaviour (Verdolin, 2006, Brown and Kotler, 2004). Within degraded habitats, the sublethal effects of preys perceived vulnerability to predation likely reduces the resilience of small mammal populations (Sheriff et al., 2009, Bleicher and Dickman, 2020, Brown et al., 1988, Creel and Christianson, 2008).

Fire scars (here-after “burnt environments”) are an increasingly common example of degraded habitat throughout Australia. The 2019/2020 fire season burnt over 23% of the country’s remaining temperate forests (Abram et al., 2021) and impacted over three billion mammals, birds, reptiles, and frogs (van Eeden et al., 2020, Boer et al., 2020). While it is difficult to estimate the direct mortality rates of these animals from the fires themselves (Nimmo et al., 2019), this season created an unprecedented 12 M Hectares of barren burnt environment (Wintle et al., 2020). As Australia’s fire regime intensifies with climate change (Flannigan et al., 2009, Bradstock, 2010), extensive burnt environments will become increasingly frequent and wide-spread.

More native small mammals may perish in the post-fire environment than during the fire itself (Doherty et al., 2015a, Firth et al., 2010, Lunney et al., 2008, Stawski et al., 2015, Fordyce et al., 2016, Kelly et al., 2010, Penn et al., 2003). This may be attributed to elevated predation pressure (McGregor et al., 2015, Leahy et al., 2016), reduced resources (Banks et al., 2011, Paquin and Coderre, 1997, Hale et al., 2022) and decreased understory complexity (Catling, 1991, Fordyce et al., 2016, Hradsky et al., 2017, Andrew et al., 2000, Fox et al., 2003). If we can protect prey from predators such as cats and foxes in these areas, we may be able to reduce prey mortality and facilitate their survival *in situ* (Banks et al., 2017), increasing their ability to repopulate regenerating habitat, and decreasing the overall impact of fires on declining small mammal populations.

Artificial refuges and the burnt environment

There has been growing interest in the potential for human-made imitations of an animal's natural refuge, hereafter "artificial refuges", to support animals in degraded environments (Homan, 2012, Lindenmayer et al., 2003, Michael et al., 2004, Cowan et al., 2021). Prior to this, the term "refuge" is generally considered refugia at the landscape scale; such as gullies that typically do not burn as intensely due to moisture content (McKenzie et al., 2004, Mackey and Lindesay, 2002, Penman et al., 2007, Swan et al., 2016), or small patches of remnant vegetation in an otherwise cleared landscape. However, artificial refuges typically explore this concept at a microhabitat scale, akin to natural refuges used by small mammals, such as rock crevices (Goldsbrough et al., 2006), grass trees (Brennan et al., 2011), and hollows (Haslem et al., 2011).

Terrestrial artificial refuge research has increased in recent years (Cowan et al., 2021), primarily motivated by protecting threatened target species (Keppers et al., 2008, Dervo et al., 2018, Grillet et al., 2010), completing fauna surveys (Hampton, 2007, Lettink et al., 2011, Bodinof Jachowski et al., 2020), or as components of biodiversity offsets (Cowan et al., 2020, Alexander et al., 2005). Many projects have resulted in positive outcomes for their target species, including improved body condition (Milne et al., 2003), decreased predation rates (Yamaguchi et al., 2005, Arthur et al., 2005), increased habitat value (Smith and Agnew, 2002) and ultimately; localised population increase (Souter et al., 2004, Arlettaz et al., 2010).

While research has considered several different animal taxa, there has been surprisingly limited research into artificial refuges for small terrestrial animals. Extensive research has been devoted to populations of birds, (Arlettaz et al., 2010, Bolton et al., 2004), arboreal marsupials (Beyer and Goldingay, 2006, Durant et al., 2009, Goldingay, 2017), bats (Flaquer et al., 2006, Smith and Agnew, 2002) and reptiles (Souter et al., 2004, Croak et al., 2013). However, to our knowledge, there are currently only two peer-reviewed publications detailing artificial refuges for Australian terrestrial mammals. Firstly, a recent study revealed that *Isodon macrourus* (Northern Brown Bandicoot) could learn to enter soft-release feeding cages with chip-automated doors, enabling exclusion of competing species or predators from feeding cages (Edwards et al., 2020). Secondly, a recent study using mesh tunnels as artificial refuges revealed that small prey species are more

comfortable foraging closer to a perceived refuge (Bleicher and Dickman, 2020). These two studies, in particular, indicate the potential for innovative artificial refuges to support Australia's small, ground-dwelling mammals.

Generally, artificial refuge projects tend to design and deploy refuges that are intended to last for many years (Lindenmayer et al., 2017). However, in the burnt environment, the need for emergency refuge is immediate, and urgent, but not long-lasting, as resprouting vegetation increases natural cover within the area (Monamy and Fox, 2000, Fox and McKay, 1981, Fox, 2022). Wire tunnels, or other heavy, permanent structures, can potentially damage the sensitive regenerating fire grounds during set-up, and then must either be removed (with great potential to damage regenerating vegetation), or else be left behind, resulting in pollution.

Here, I designed and executed the first field test of an innovative, flat-packed, recycled cardboard refuge for fauna after fires, which is designed to biodegrade away within approximately 12 months. These refuges, termed "Habitat Pods", have been designed through a collaborative project between Dr Alexandra Carthey of Macquarie University, and Alex Goad, of the Reef Design Lab in Melbourne.

Habitat Pod field trial

I conducted a field trial of Habitat Pods at the site of an out-of-control prescribed burn in Marramarra National Park, which sits in the Hawkesbury River Catchment, 40 km to the northwest of Sydney, NSW. The burn happened in September 2021 and provided an ideal opportunity to field test the habitat pods as refuges for ground-dwelling fauna after a fire.

Habitat Pods are intended to partially supplement microhabitat refuges for ground-dwelling fauna in the burnt environment by mimicking understory vegetation cover. Unlike typical artificial refuges, which replicate nesting or roosting sites, Habitat Pods are designed to facilitate natural prey behaviour and movement across the landscape while enhancing available cover. Notably, Habitat Pods are not targeted towards specific species, but rather towards all terrestrial small animals that benefit from complex understory. Habitat Pods are intended to decrease predator hunting success and support prey populations *in situ*, thereby supporting local species persistence.

The targets of this study were ground-dwelling or semi-arboreal mammals within the 35-5500g Critical Weight Range (Chisholm and Taylor, 2010, Johnson and Isaac, 2009). While Habitat Pods are intended to benefit a broader suite of species than these, the scope and timeframe of the Master of Research Project required that I limit my focus to a particular taxon. Ground-dwelling critical weight range mammals are an important focus for conservation ecology research because of their vulnerability to cats and foxes, as well as other key habitat threats. Within the Hawkesbury River Catchment, several terrestrial mammals fit within this criterion (Appendix. A); being members of the Muridae, Dasyuridae, Peramelidae, Burramyidae and Pseudocheiridae families.

These family groups typically rely on fire-sensitive elements of the landscape for shelter and food resources. In addition to complex understory, ecological features required include leaf litter (Dickman and Steeves, 2004, Fox and McKay, 1981), logs (Hradsky et al., 2017, Johnstone et al., 2011, Sutherland and Dickman, 1999, Maitz and Dickman, 2001, Mowat et al., 2015), rushes (Maitz and Dickman, 2001, Kearney et al., 2007) and Xanthorrhoea spp. (Spencer et al., 2005, Stokes et al., 2004, Swinburn et al., 2007, Tulloch and Dickman, 2006). While some of these mammals are semi-arboreal (Dasyuridae, Burramyidae and Pseudocheiridae) they are nevertheless impacted by fire, which removes

tree hollows (Kearney et al., 2007, Matthews et al., 2017, Lindenmayer et al., 2008a, Flanagan-Moodie et al., 2018) and mid-level canopy, causing individuals to spend more time on the ground (Sutherland et al., 2004). Previous research into these family groups indicates that local populations decline in burnt environments (Penn et al., 2003, Hradsky et al., 2017, Russell et al., 2003), hence I included them in this research.

Ultimately, this field trial aimed to compare burnt and unburnt environments in terms of the availability of natural refuges, ground-level vegetation cover, temperature, and activity of small mammals and their predators (cats and foxes). I also wanted to determine whether small mammals would use the habitat pods, and whether the habitat pods would influence the activity or behaviour of small mammals or their predators. Finally, I wanted to record the process of Habitat Pod biodegradation in the field.

I had four key hypotheses.

1. Burnt sites would have more varied temperatures, lower vegetation cover, and fewer available natural refuges than unburnt sites.
2. Prey activity would be lower in burnt than unburnt environments, while predator activity would show the opposite pattern (higher in burnt than unburnt).
3. If prey perceive increased predation risk in burnt environments, then prey would be more fearful in burnt than unburnt environments, showing more vigilance, less foraging, and less relaxed behaviour (such as grooming).
4. If prey perceive Habitat Pods as refuge, then adding Habitat Pods should reduce the size of any differences in prey activity and behaviour between burnt and unburnt sites.

Methods

To assess effects of Habitat Pods on small mammal and predator activity and behavior, and to observe their biodegradation in the field, I undertook a field study using a BACI design (Before-After-Control-Impact; (Green, 1979, Stewart-Oaten et al., 1986). The field study ran for 21 weeks (23 December 2021 to 20 May 2022) in corresponding unburnt and burnt habitats. The “Before” period spanned 3 weeks before Habitat Pods were installed (the “Impact”) at designated sites on 13 January 2022. I chose a BACI experimental design to distinguish the influence of Habitat Pods from confounding natural changes in species composition associated with the burnt recovery (Christie et al., 2019, Johnson, 2002).

Study area

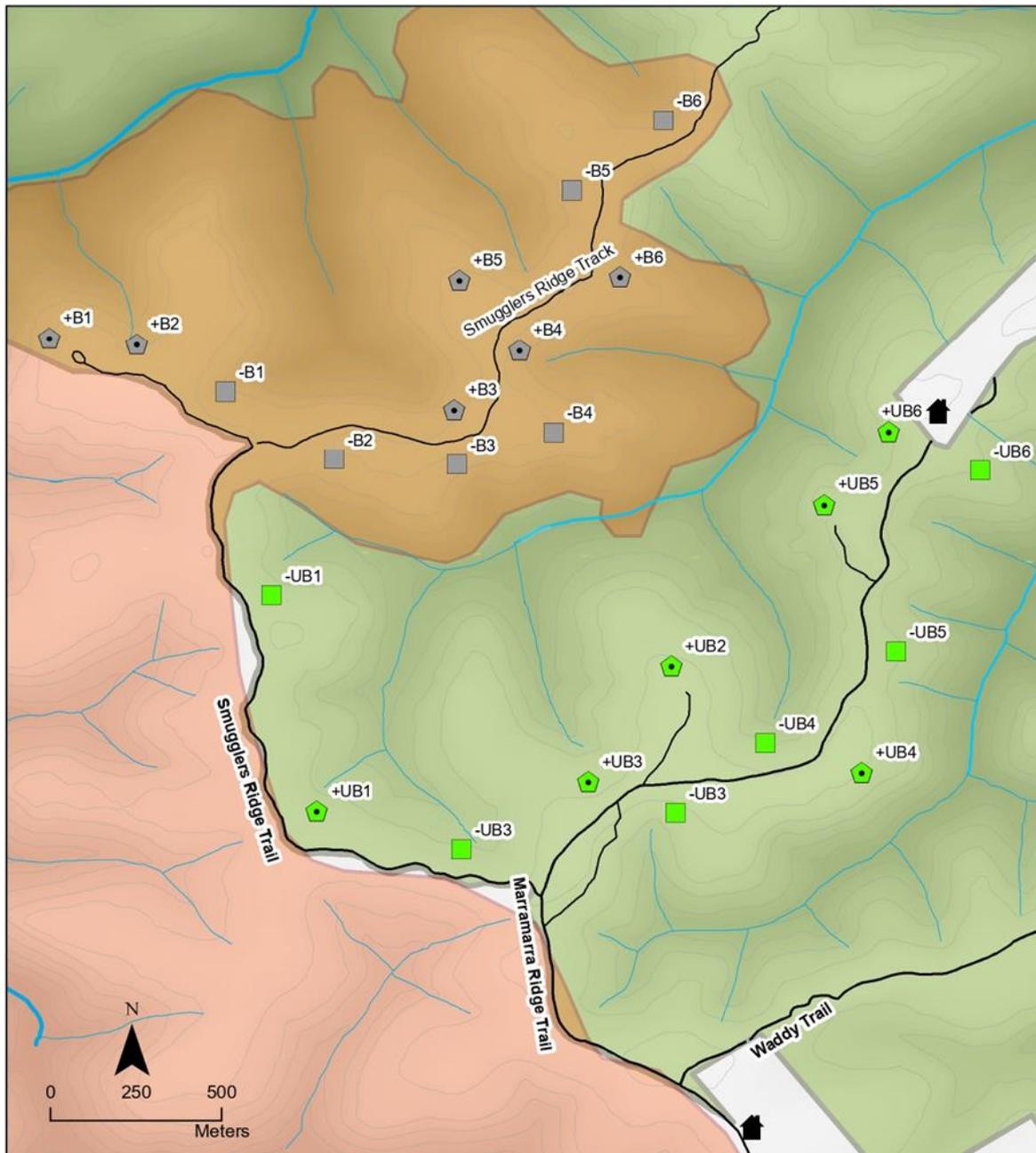
Marramarra National Park lies approximately 40km to the northwest of Sydney CBD (NPWS, 2016) within the Hawkesbury River Catchment of NSW Australia (33° 33' 13.6584" S, 151° 3' 41.7888" E; Fig.1), This temperate region is characterised by dry sclerophyll forest on undulating sandstone ridges and valleys (Keith and Simpson, 2012). The study coincided with an exceptionally wet period associated with the La Nina phase of El Niño-Southern Oscillation, with the nearest weather station (Terry Hills, 33° 42' 3.6" S, 151° 12' 36" E) recording close to 1000mm more than the average for the study period (Bureau of Meteorology, 2022). The study area has not been logged (T. Burton, *Pers. Comm*, November 25, 2021)

Twenty-four 10 x 10 m study sites were established along Marramarra Ridge and Smugglers Ridge within the south-eastern corner of Marramarra National Park (Fig.1). An elevation between 200-220 AMSL was chosen to target the ridgelines, which are typically the most severely burnt by wildfires in eastern Australia (Penman et al., 2007). Sites were established at least 70m distance from roadways, which can act as movement corridors for introduced predators (Read et al., 2015, Hernandez-Santin et al., 2016) and 200 m from private residences, which are associated with the presence of commensal rodents such as *Mus musculus*, *Rattus rattus*, and *Rattus norvegicus* (Hall et al., 2016, Van Dyck et al., 2013). All sites were selected to be at least 150 m apart, which was deemed appropriate based on the Muridae maximum average home range of 1 Ha (Maitz and Dickman, 2001).

This resulted in an average Habitat Pod density of approximately 1 site (10 x 10m, containing two clusters of eight pods) per 1.5 Ha.

Twelve of the sites (hereafter “Burnt sites”) were within the 190 Ha burnt area. An out-of-control prescribed burn burnt this area much more severely than intended on 16th September 2021. Ground cover was sparse, and regeneration was minimal by the start of this study (approximately 10 weeks after burning; Fig 7, Table 3). The remaining twelve sites (hereafter “Unburnt sites”) were outside of the 2021 burnt area and had well-developed understory vegetation. Six randomly selected burnt sites, and six randomly selected unburnt sites received pods on 13th January 2022. This resulted in four treatment groups: Burnt with Pods (B+), Burnt without Pods (B-), Unburnt with Pods (UB+) and Unburnt without Pods (UB-), each with six replicates (N = 6).

I used the following datasets within ArcGIS Desktop 10.8 to characterise vegetation community type, elevation, aspect, distance from drainage lines and distance from private residence for each site, to ensure sites were as similar as possible: NPWS Fire History (Department of Planning and Environment, 2022a), NPWS Estate Boundaries (Department of Planning and Environment, 2022b), Digital Elevation Model (DEM) 5 Metre Grid (Geoscience Australia, 2015) and the Vegetation Community map (NSWmap_v3_03_3848) produced by the Vegetation Map of Marramarra National Park, Muogamarra Nature Reserve and Maroota Historic Site (Lembit et al., 2002). All datasets were accessed through Seed Data Portal (<https://www.seed.nsw.gov.au/>, November 2021).



- | Legend | | Treatments | |
|--------|-----------------------------------|------------|----------------------|
| | Marramarra National Park Boundary | | Burnt with Pods |
| | Fiddletown Wildfire | | Unburnt with Pods |
| | Drainage Line | | Burnt without Pods |
| | NPWS Roads | | Unburnt without Pods |
| | NPWS Walking Tracks | | |
| | Private Residence | | |



Fig. 1. Map showing study site distribution throughout the south-eastern corner of Marramarra National Park. Inset shows National Park location, Galston, NSW, Australia.

Habitat Pod structure

Habitat Pods are constructed of recycled cardboard and are transported flat and assembled on site. When assembled, Habitat Pods (hereafter “pods”) are hexagonal pyramids, 0.6(w) x 0.6(d) x 0.6(h) m in size, reinforced by internal cardboard structures which form internal chambers connected by passageways (Fig. 2). For this field trial, pod sites received eight Habitat Pods, arranged in two clusters of four at opposite ends of the sites (Fig. 6). The clusters were arranged so that Habitat Pod grounding flaps formed a corridor through the cluster (Fig.2). Pods were anchored using 10 commercially available biodegradable tent pegs (Survival Storehouse, NSW, Australia) along the grounding flaps.

Habitat Pod external and internal cardboard structures have an array of holes ranging in diameter from 10 mm to 100 mm. Previous literature indicates that the small mammals expected to be present within Marramarra National Park will use entrance holes of this size (*Cercartetus nanus* <30 mm, *Antechinus* spp. 30 mm to >80 mm. and *Pseudocheirus peregrinus* > 80 mm) (Beyer and Goldingay, 2006). Hole sizes are also larger than the average body diameter of bandicoots (Peramelidae; *Pers. comm.* for body size: Australian Wildlife Conservancy 2021). All holes are circular for maximal access.

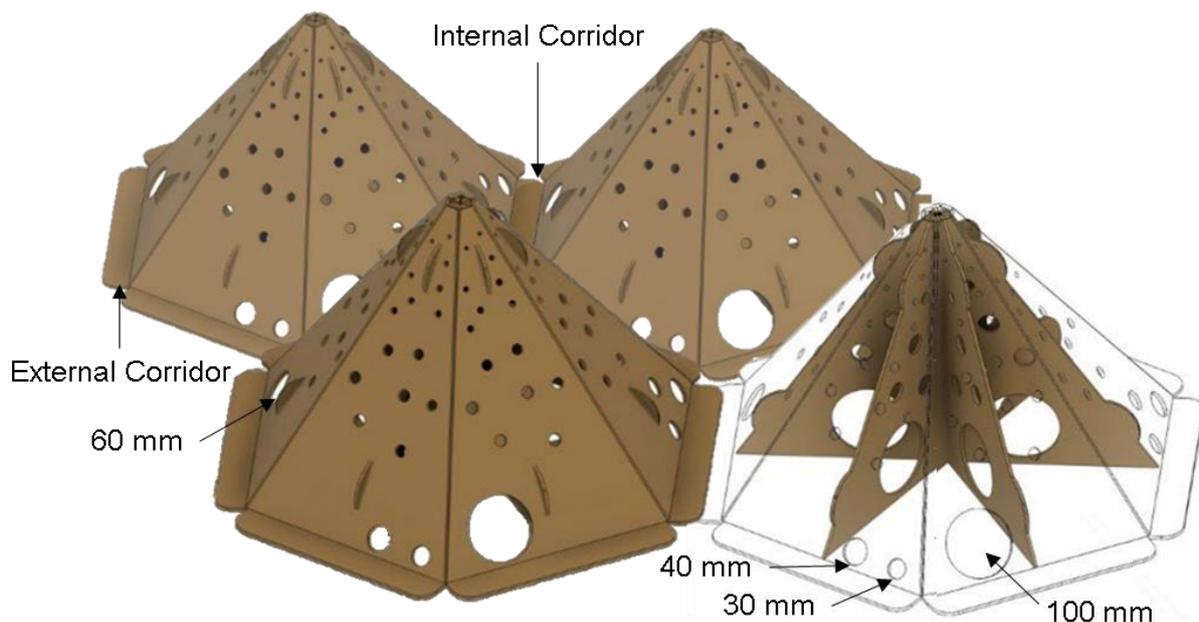


Fig. 2. Diagram of Habitat Pod cluster as seen from horizontal cameras, displaying structural entrances and external and internal corridors created by grounding flaps. Diagram modified from Reef Design Lab (www.reefdesignlab.com). Treatments receiving Habitat Pods received two clusters per site.

Ecological conditions

This field trial extended across 21 weeks, with camera footage being collected throughout the projects entirety (with results averaged into 3-week time periods for certain analyses) and field surveys being conducted at various designated times (Fig. 4).

If fire consumed the majority of understory vegetation, burnt sites were expected to contain less cover for prey avoiding predation. To quantify vegetation cover I chose to use a method specifically developed to estimate how well concealed prey are from predators in a given habitat: the Quadrant Cover Method (Glen et al., 2010). This method has previously been used to assess small mammal vulnerability to predation within burnt environments (Lees et al., 2022, Fordyce et al., 2016).

A 2 m circular quadrant was laid on the ground and two observers estimated visibility scores of an imagined bush rat (*Rattus fuscipes*) positioned in the epicenter of the circle, from the eyeline of a fox (*V. vulpes*) looking inwards from the circle's circumference for each quadrant (Fig.3). Scores were as follows: 0 = completely visible, 10 = partially obscured, 20 = completely obscured (Glen et al., 2010). A fifth score estimated visibility of the imaged bush rat from above, intended to represent aerial predation risk. This resulted in five scores (out of 20) being recorded by each observer, giving a total score out of 100. This process was repeated at five randomly selected locations within each site, and the five scores were averaged to give a single score (out of a possible 100) for each of the 24 sites. The vegetation cover surveys were conducted during February and April (Fig.4).

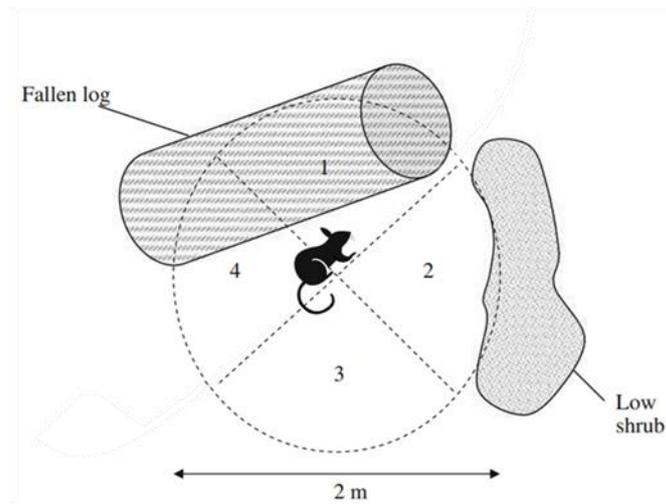


Fig. 3. Figure modified from Glen et al. (2010), showing the sampling circle with four quadrats. Researchers estimate visibility of a bush rat-sized prey animal at the centre of the circle (out of 20), once from each quadrant, and once from above (giving a total score out of 100).

The availability of natural refuges such as logs, and their associated hides may affect the appeal of artificial refuge provided by Habitat Pods. I counted the number of natural refuges (logs) within each 10 x 10 m site. Fallen timber was classified as a log if either of the end diameters was greater than 10 cm, because *A. flavipes* only shelter in logs with diameter > 10 cm (Flanagan-Moodie et al., 2018). The number of potential hides (hereafter log-hides) provided by each log was quantified. Log-hides were defined as any enclosed area, either within the log itself or created by the log lying on a surface, that had an entrance greater than 20 mm and were greater than 20 mm deep. Surveys for logs and their associated log-hides took place in late April (Fig.4).

Ambient temperature (External) measurements were collected by a Thermochron iButton logger (DS1921G, Maxim Integrated Products, Sunnyvale, CA, USA) at the centre of every site, programmed to record temperatures every half an hour, at an accuracy of ± 0.5 °C. Data was collected simultaneously across every site during two three-week periods (26/01/2022 to 17/02/2022 and 7/03/2022 to 28/03/2022). Collecting and averaging data from two different periods provided a general overview of microclimate conditions across these sites.

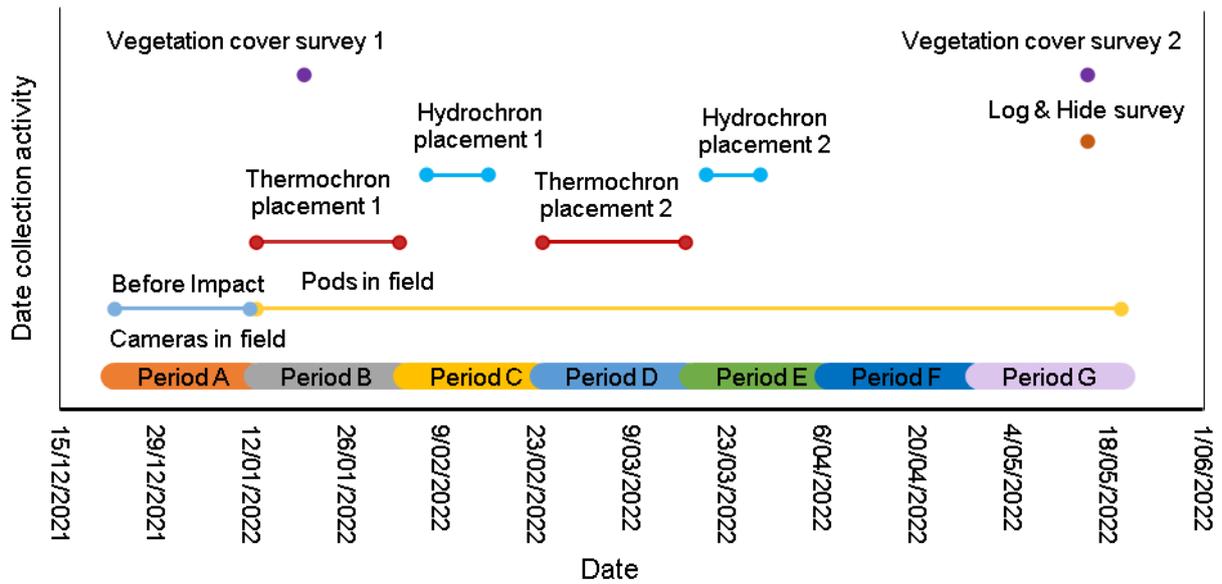


Fig. 4. Timing of key elements of the field campaign conducted for this study; eight 3-week time periods (A to G), timing of Thermochron and Hydrochron iButton placements, vegetation cover surveys, and the Log and Log-hide survey.

Cameras

Each of the 24 sites received two motion and heat-activated cameras (Browning Force Patriot FHD Trail Camera ©). These were deployed for 3 weeks before pod deployment (23 December 2021). Data collection ended 18 weeks after pod deployment (20 May 2022). At the sites with pods (B+, UB+), a camera was positioned 60 cm above the ground and faced horizontally towards the Primary Cluster (Fig.6), looking along an internal corridor, with the raised camera stake aligned in the top center area of the frame (Fig. 6). The raised camera was positioned directly above the Primary Cluster facing downward at a 100° angle, to provide an aerial view of all entrances and exterior pod corridors. This arrangement was replicated at sites without pods (B-, UB-), ensuring that the horizontal camera view frame always had the raised camera stake positioned in top center.

Cameras were set to record 10 second videos when movement was detected, with a minimum of 1-second interval before they would re-trigger. Because all small mammals of interest to this study are predominantly nocturnal (Strahan, 2002), analysis was limited to footage from one hour before astronomical twilight and one hour after dawn. Some Dasyruidae (*A. swainsonii*, *A. flavipes* (Menkhorst and Knight, 2001, Matthews et al., 2017)), as well as *R. lutreolus*, may occasionally be diurnally active, but this is rare in burnt areas (Matthews et al., 2017, Kearney et al., 2007, Flanagan-Moodie et al., 2018). Video quality was set to High and night exposure was set to Power Save. Motion detection sensitivity was set to normal, after excessive false trigger rates during pilot trials.

Footage analyses

I used Behavioural Observation Research Interactive Software (BORIS) to score the footage obtained from the field cameras, using an ethogram I designed for this study (Table 1). BORIS is a desktop-based program that allows the viewer to identify subjects and score their behaviors (Friard and Gamba, 2016). I used BORIS to record prey (Muridae, Dasyuridae, Peramelidae, Burramyidae and Pseudocheiridae) and predator (Vulpes, Felidae) activity by recording the average number of visits per period per treatment. The number of times prey species displayed vigilance, foraging and grooming were recorded, as were displays of investigative or destructive behavior by predators (Fig. 5) I also calculated the average duration of time spent at different site types by different fauna. Results for behavioral displays and duration of stay were averaged to site level per

sampling period, and then averaged across treatment group for the entire project duration (Fig.5, Fig.12, Fig.13).

When both cameras had captured the same independent trigger, only footage from the camera angle most suited to behavioral analysis was used. There was one instance where more than one individual appeared within a camera shot (mother and juvenile Pseudocheiridae). For this footage, only activity of the juvenile was analysed as it was more active.

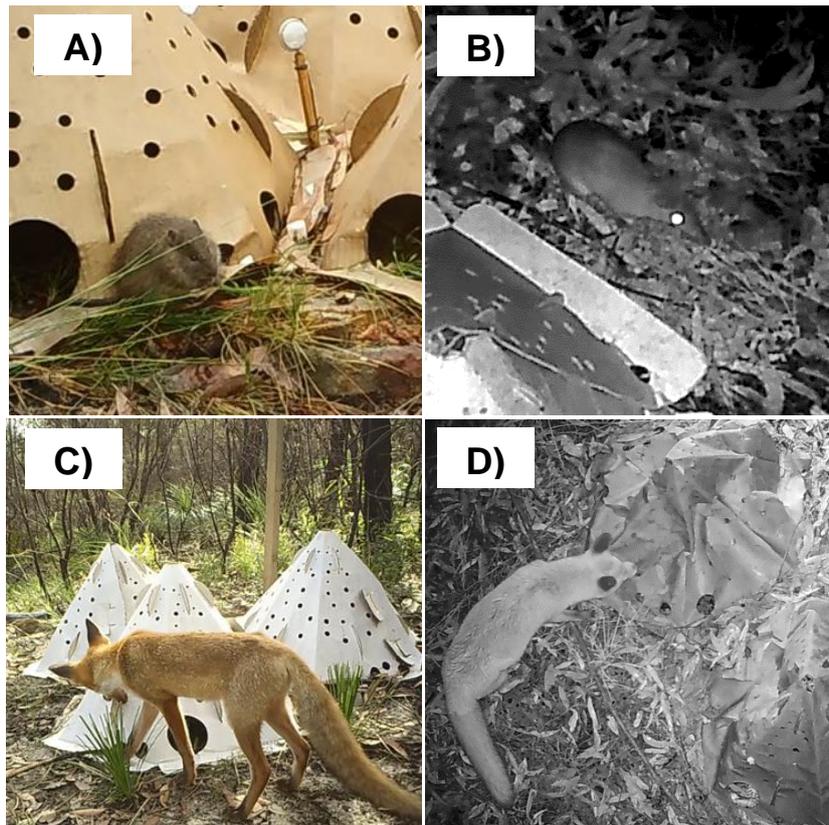


Fig. 5. Examples of typical A) Foraging (Muridae member, likely *Rattus fuscipes*), B) vigilance (Peramalidae member, likely *Perameles nasuta*), C) destructive (Canidae member, *Vulpes vulpes* and D) Investigative behaviour (Canidae member, *V. vulpes*), as described in ethogram (Table 1)

Table 1. Ethogram of behaviour displayed by predator or prey during independent visits.

Behaviour Category	Description
Foraging	Digging or ingesting food. Animals may also be looking for food, as shown by holding their head angle below horizontal and moving slowly. May crouch on hind legs and use both hands to hold food.
Grooming	Pawing at or licking fur, rubbing paws over body parts whilst staying in one location.
Vigilance	The animal is still. Head angle above horizontal, body position can be crouched, upright or extended. Scanning side to side. The animal does not forage or groom but may be chewing.
Destruction	Chewing on/destroying/ attempting to destroy pods. May try to uplift/dig into/ gain access to refuges.
Investigate	Inspecting pods or experiment equipment as indicated by the body and head posture directed towards item of interest. May be looking or sniffing (as indicated by vertical head waggle). May put nose in holes of Habitat Pods. If inspecting vegetation, movements are classified as foraging.
Enters Pod	Seen emerging or exiting Habitat Pod. Back and front legs were within internal chamber. Entrance size is recorded (100, 60, 40, 30 mm or underneath structure).

Habitat Pod design assessment

Whenever members of each Prey family group (Muridae, Dasyuridae, Peramelidae, Burramyidae and Pseudocheiridae) were seen on camera footage entering or exiting the Habitat Pods, I recorded the entrance chosen.

To determine the effect of Habitat Pods on microclimates, temperature (C°) and relative humidity (RH%) measurements were taken at different locations. As with ambient temperatures, all microclimate temperatures were measured using Thermochron iButton logger (DS1921G, Maxim Integrated Products, Sunnyvale, CA, USA). Humidity was measured using iButton Hydrochron loggers (± 0.5 °C, iButton DS1923, Maxim Integrated Products, Sunnyvale, CA, USA). These microclimates were inside a randomly selected Habitat Pod (hereafter "Internal", along an internal corridor (hereafter "Corridor") and within the middle of each site ("External"). Temperature measurements were collected simultaneously across every site during two separate three-week periods (26 January 2022 to 17 February 2022; 7 March 2022 to 28 March 2022) and averaged to provide a general overview of microclimate conditions at these sites. Due to limited availability of Hydrochron iButtons, only two sites (each with pods; one burnt, one unburnt) had Hydrochron iButtons installed for two eight-day periods (8 February 2022 to 16 February 2022, 20 March 2022 to 28 March 2022) (Fig. 4).

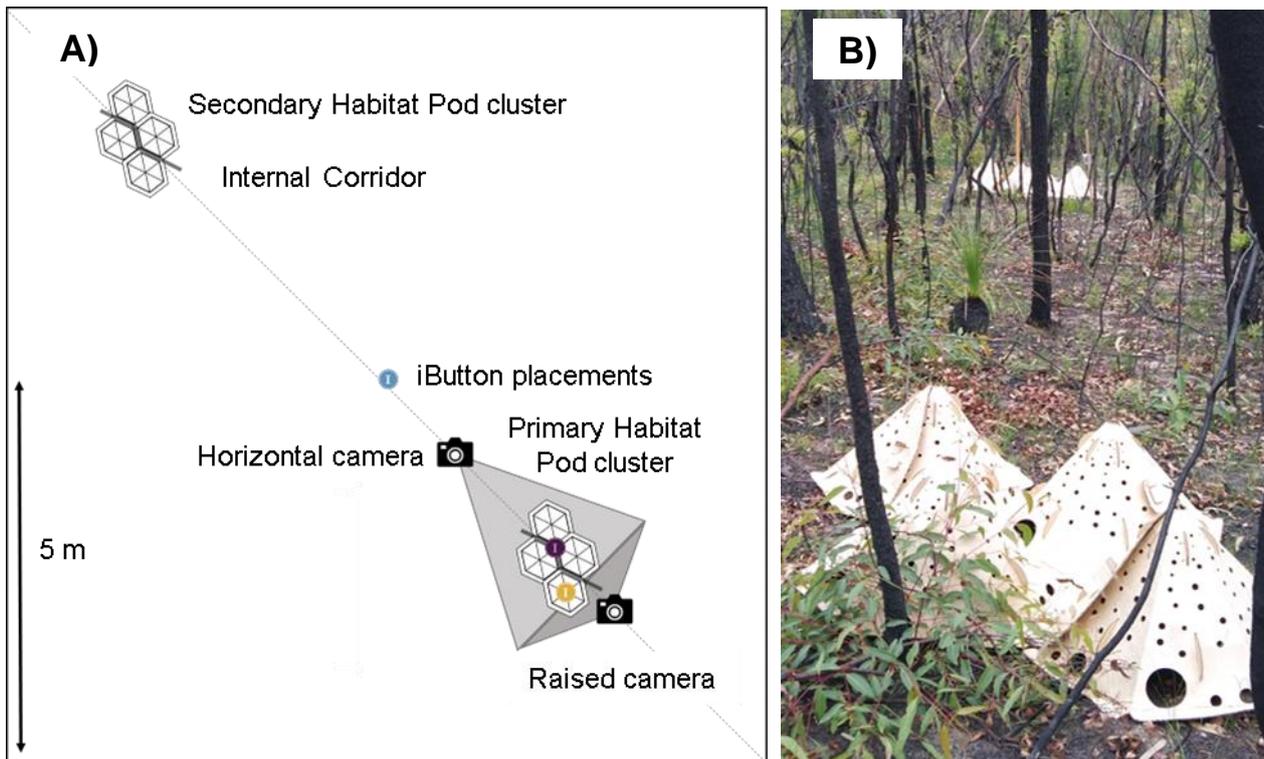


Fig. 6. Schematic (A) and photo (B) of site set-up. All camera footage was collected at the Primary Habitat Pod Cluster. The horizontal camera was positioned to face down the cluster's Internal Corridor. Microclimates monitored by iButtons shown by coloured circles in (A); positioned in site centre (External), Internal Corridor (Corridor) and Internally (Internal).

Habitat Pods are intended to biodegrade within approximately 12 months. Pod degradation was visually assessed approximately every 21 days. Each Habitat Pod at a site was scored out 5 (Table 2), where 1 denoted no degradation and 5 denoted collapse. These eight scores were averaged to generate a site score. The scoring system was adopted from a concurrent Habitat Pod study at North Head in Sydney (*Pers. comm*, A. Rana, PhD candidate, University of Sydney), to allow comparison of biodegradation across studies.

Table 2. Scoring system developed by A. Rana to measure degradation of Habitat Pods. Site score was averaged score of each Habitat Pod.

Degradation definition	Example
Level 1 – Condition as per deployment. Cardboard still light brown, standing strong, no rips or water/sun damage	
Level 2 – Structure still strong and intact, no rips through multiple layers of cardboard, but pods white in colour and outer layer of cardboard appears slightly shrivelled and/or minimal peeling from water/sun damage	
Level 3 – Structure still upright but integrity compromised by rips through multiple layers of cardboard and/or outer layer shrivelled and peeling from water/sun damage	
Level 4 – Structures still partially standing and in original position but starting to collapse or degrade, no longer upright, inside supporting structures compromised, large rips through multiple layers and outer layers damaged from sun/water exposure	
Level 5 – Pods flat on the ground, cardboard layers collapsed on one another, cardboard ripped apart, pods no longer in original positions	

Data Analyses

Analyses were conducted in Primer-E v.7 (Plymouth Marine Laboratory). I used univariate Permutational Analyses of Variance (PERMANOVA; (Anderson et al., 2008)) to test for independent and interactive effects of fire and pods on environmental conditions at sites, and on the activity and behavior of prey and predators.

Analyses of time was based on the seven 3- week camera sampling periods (Fig.4). Period A formed the “Before” Impact period, prior to Habitat Pods being deployed at designated sites on 13 January 2022. Remaining six sampling periods (B-G) represented “After” impact.

Analyses of vegetation cover, which was sampled twice following pod installation, had three factors: Time (2 levels; Before/After), Fire History (fixed; 2 levels; Burnt/Unburnt) and Pod Treatment (fixed, 2 levels; Pods/No pods). Analyses of the average and range in temperatures recorded in plots, away from pods (sampled twice but averaged into one score), and of log counts and log hides (sampled once), had the factors Fire History and Pod Treatment. Additional analyses, run only on data obtained from sites with pods, compared average temperatures and ranges in temperature recorded between the inside of pods, between pods, and the habitat away from pods (2 factors: Microhabitat, Fire History).

Analyses of predator and prey activity (average number and duration of independent visits), each prey behavior (grooming, foraging, vigilance) and each predator behavior (destructive, investigative) had four predictive factors: Time (fixed, 7 levels; 1 before and 6 after pod installation; see Fig. 4), Fire History, Pod Treatment and Site (nested within Fire History and Pod Treatment as sites were repeatedly sampled).

As mentioned, all small mammal family groups (Muridae, Dasyuridae, Peramelidae, Burramyidae and Pseudocheiridae) were grouped into “Prey” for most analyses due to insufficient data for separate analyses. Similarly, *Vulpes vulpes* and *Felis catus* were grouped into “Predators”.

Results

A total of 7,104 camera trap nights were achieved throughout this project. There were 587 independent triggers, across all treatment groups (B-, B+, UB-, UB+). Prey species constituted the majority of all triggers: 164 Muridae, 155 Dasyuridae, 118 Peramelidae, 68 Pseudocheiridae and 50 Burramyidae. Predator independent triggers comprised 4 Felids (*Felis catus*) and 28 Canids (*Vulpes vulpes*).

In keeping with changing expectations around how statistical analyses are presented and interpreted, all statistics are discussed using the language of evidence (Muff et al., 2021).

Ecological conditions

As expected, there was substantially less vegetation cover at burnt than at unburnt sites (Pseudo- $F_{1,40} = 76.32$, $p(\text{perm}) = 0.001$; Fig. 7, Table 3). This pattern was independent of Pod Treatment (Pseudo- $F_{1,40} = 0.19$, $p(\text{perm}) = 0.69$; Table 3), and consistent across the two sampling times (Pseudo- $F_{1,40} = 2.58$, $p(\text{perm}) = 0.12$; Table 3). There was no discernible regrowth over the 4 months between sampling periods (Pseudo- $F_{1,40} = 1.74$, $p(\text{perm}) = 0.21$; Fig. 7, Table 3).

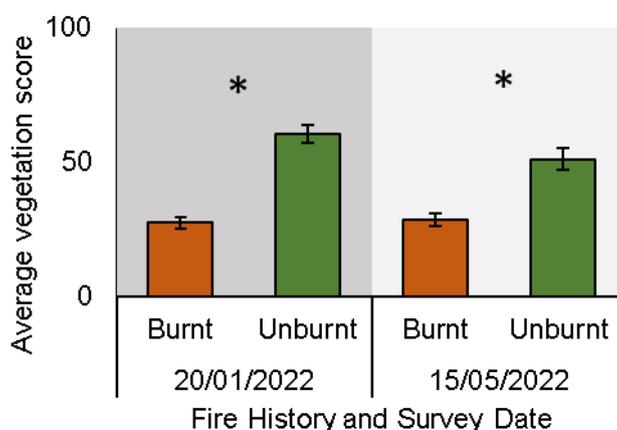


Fig. 7. Average (\pm SE) vegetation cover scores produced by the Quadrant Cover Method (100 = animal completely obscured within every quadrant and from above), for burnt and unburnt sites, at two sampling times. * Indicates significant difference ($p(\text{perm}) = 0.001$) between Burnt and Unburnt areas. Scores are presented as averaged across Pod Treatments as these did not differ in vegetation cover. N = 6 sites per treatment.

Table 3. Results of a univariate PERMANOVA analysis testing for spatial variation in vegetation cover score (calculated using the Quadrant Cover Method) among sites varying in Fire History (burnt vs. unburnt) and in Pod Treatment (present vs. absent), at each of two sampling times (20/1/2022; 15/5/2022). Bold text denotes significant result at $\alpha = 0.05$.

Source	<i>df</i>	Understorey cover		
		<i>MS</i>	<i>pseudo-F</i>	<i>P(perm)</i>
Time	1	5313.00	1.74	0.21
Fire History	1	233100.00	76.32	0.001
Pod Treatment	1	379.69	0.12	0.74
Time x Fire History	1	7879.70	2.58	0.12
Time x Pod Treatment	1	4.69	0.001	0.98
Fire History x Pod Treatment	1	567.19	0.19	0.69
Time x Fire History x Pod Treatment	1	1054.70	0.35	0.55
Error	40	3054.30		

In contrast to vegetation cover, log counts did not vary among sites according to Fire History (Pseudo- $F_{1,20} = 0.15$, $p(\text{perm}) = 0.71$; Table 4) or Pod Treatment (Pseudo- $F_{1,20} = 0.15$, $p(\text{perm}) = 0.74$); Table 4). Despite this, average log-hide count (Fig. 8) was significantly influenced by the interaction of Fire History and Pod Treatment (Pseudo- $F_{1,20} = 7.55$, $p(\text{perm}) = 0.013$; Table 4), with significantly fewer hides at the burnt site with pods than in any of the other treatments (Fig. 8).

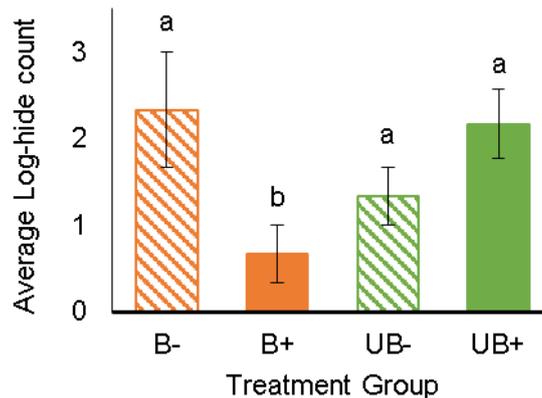


Fig. 8. Average (\pm SE) Log-hide count at burnt (B) and unburnt (UB) sites, with (+) and without (-) pods. Letters (a, b) above bars represent the results of PERMANOVA post-hoc Monte Carlo test, bars with different letters are significantly different from one another. N = 6 sites per treatment.

Table 4. Results of a univariate PERMANOVA analyses testing for spatial variation in the abundance of Logs and Log-hides between sites varying in Fire History (burnt vs unburnt) and Pod Treatment (present vs absent). Bold text denotes significant result at $\alpha = 0.05$. Significant relationships further investigated by PERMANOVA *post hoc* Monte Carlo test.

Source	df	Average Log count			Average Log-hide count		
		MS	pseudo-F	P(perm)	MS	pseudo-F	P(perm)
Fire History	1	0.38	0.15	0.71	0.38	0.30	0.58
Pod Treatment	1	0.38	0.15	0.74	1.04	0.84	0.39
Fire History x Pod Treatment	1	9.38	3.69	0.07	9.38	7.55	0.013
Error	20	2.54			1.24		

There were no differences between burnt and unburnt sites in the mean ambient temperatures recorded by External iButtons (Pseudo- $F_{1,43} = 0.19$, $p(\text{perm}) = 0.65$; Table 5). There was, however, weak evidence (Pseudo- $F_{1,43} = 3.43$, $p(\text{perm}) = 0.08$; Table 5) that the burnt environment exhibited slightly more variation in ambient temperature (range) than the unburnt area.

Table 5. Results of a univariate PERMANOVA analyses testing for spatial variation in the average and range in temperature (°C) recorded by External iButtons between 26/01/2022 to 17/02/2022; 7/03/2022 to 28/03/2022. External iButtons were placed away from pods at sites varying in Fire History (burnt vs unburnt) and Pod Treatment (present vs absent).

Source	df	Average (°C)			Range (°C)		
		MS	pseudo-F	P(perm)	MS	pseudo-F	P(perm)
Fire History	1	0.27	0.19	0.65	102.82	3.43	0.08
Pod Treatment	1	0.24	0.17	0.67	6.57	0.22	0.64
Fire History x Pod Treatment	1	0.07	0.05	0.83	10.82	0.36	0.54
Error	43	1.4			29.98		

Fauna activity and behaviour

Five prey families (Muridae, Dasyuridae, Peramelidae, Burramyidae and Pseudocheiridae) visited my sites, with the relative proportions of each family visiting differing among sites (Fig. 9A). Canidae (*Vulpes vulpes*, foxes) were the most observed predator, with only four *Felidae* (*Felis catus*, cat) sightings in total over the 21-week sampling period. Cats were only observed at burnt sites, while foxes were seen at both burnt and unburnt sites (Fig. 9B).

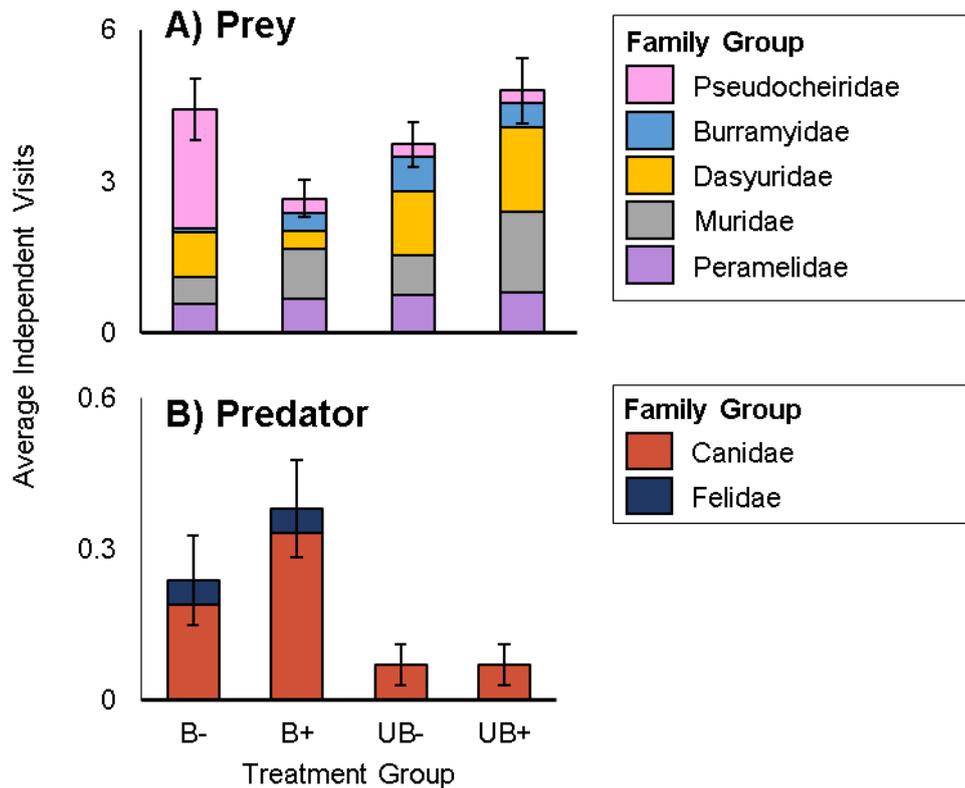


Fig. 9. Relative contribution of different prey and predator families to the distribution of independent visits at burnt and unburnt sites, with and without pods. Bars show the mean (\pm SE) count of independent visits by Family, for prey (A) and predators (B) to sites varying in Fire History (Burnt: B, Unburnt: UB) and Pod Treatment (present [+], absent [-]). Visits are pooled across all sampling periods (Periods A-G). N = 6 sites per treatment.

There was only weak evidence for lower prey activity (number of independent visits) at burnt compared to unburnt sites (Pseudo- $F_{1,20} = 4.28$, $p(\text{perm}) = 0.06$; Table 6, Fig. 10A). There were no differences in prey activity through Time (Pseudo- $F_{6,120} = 1.39$, $p(\text{perm}) = 0.21$; Table 6, Fig. 10A), or according to Pod Treatment (Pseudo- $F_{1,20} = 0.97$, $p(\text{perm}) = 0.32$; Table 6, Fig. 10.A), nor any interactions among factors (Fig. 10A). There was strong evidence for high variability in prey activity among sites (Pseudo- $F_{20,120} = 7.16$, $p(\text{perm}) = 0.001$; Table 6, Fig. 10A).

In contrast, there was moderate evidence for greater predator activity (more independent visits) at burnt than at unburnt sites (Pseudo- $F_{1,20} = 5.09$, $p(\text{perm}) = 0.03$; Table 6, Fig. 10B). Independent visits by predators also increased over Time (Pseudo- $F_{6,120} = 2.59$, $p(\text{perm}) = 0.02$; Table 6, Fig. 10B). Pods had no effect on predator activity at either burnt or unburnt sites (Pseudo- $F_{1,20} = 0.25$, $p(\text{perm}) = 0.64$; Table 6, Fig. 10B), nor were there any interactions among factors (Fig. 10B). As with prey, there was strong evidence for high variability in predator activity among sites (Pseudo- $F_{20,120} = 1.995$, $p(\text{perm}) = 0.001$; Table 6, Fig. 10B).

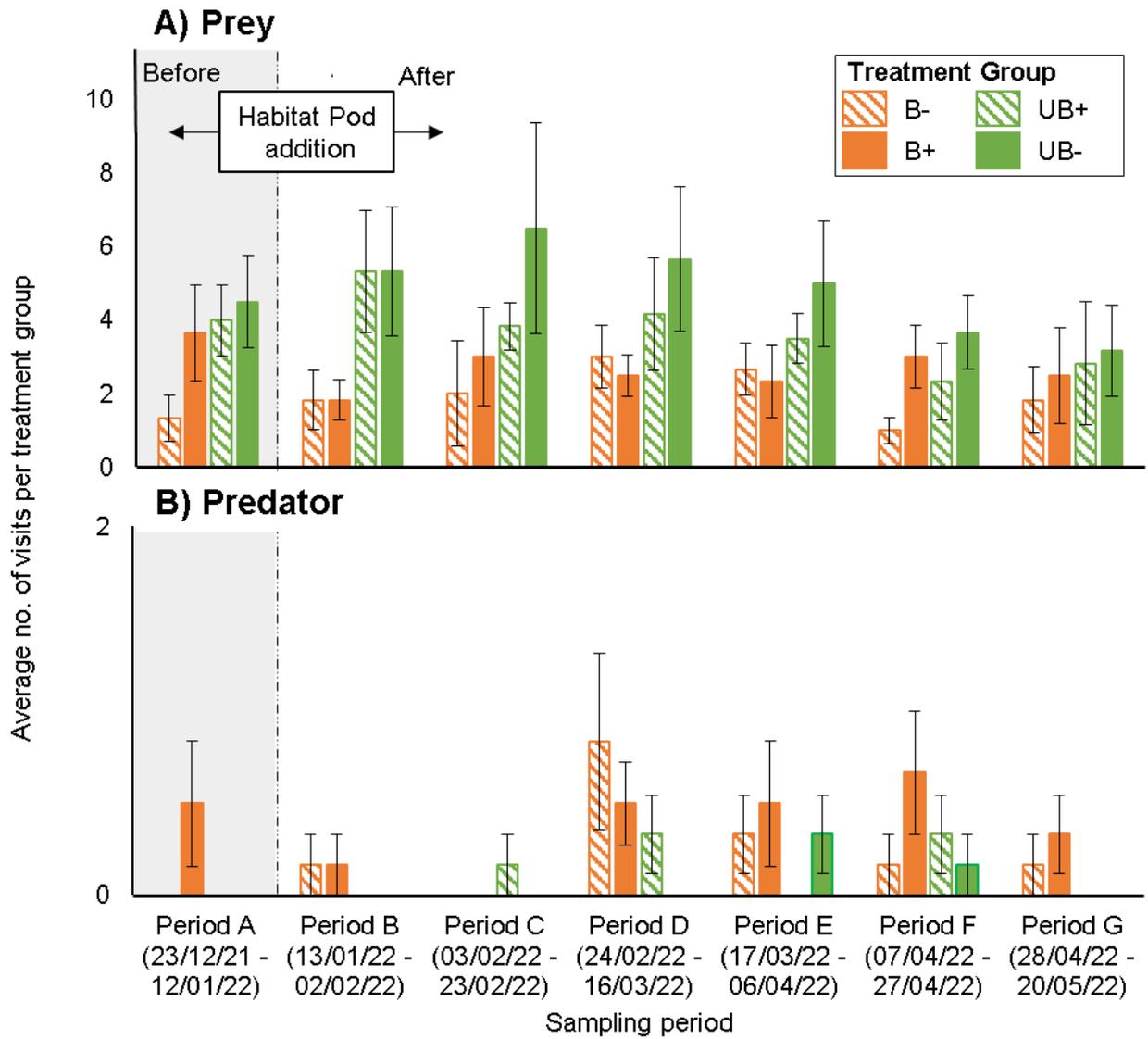


Fig. 10. Average (\pm SE) count of independent visits by prey (panel A) and predators (panel B) to burnt (B) and unburnt (UB) sites, with (+) and without (-) Habitat Pods, within periods before (shaded area) and after (unshaded area) pod installation. N = 6 sites per treatment.

Table 6. Results of a univariate PERMANOVA analysis testing for differences in activity (number of independent visits) for prey and predators. Visits were compared among sites varying in Fire History (burnt vs unburnt) and Pod Treatment (present vs absent), before (Time; period A) and after (Time; periods B-G) deployment of pods. Sites, nested in Fire History and Pod Treatment, were repeatedly sampled through Time. Bold font denotes significant result at $\alpha = 0.05$.

Source	df	Prey Activity			Predator Activity		
		MS	<i>pseudo-F</i>	<i>P(perm)</i>	MS	<i>pseudo-F</i>	<i>P(perm)</i>
Time	6	7.26	1.39	0.21	0.49	2.59	0.02
Fire History	1	160.10	4.28	0.06	1.93	5.09	0.03
Pod Treatment	1	36.22	0.97	0.32	0.10	0.25	0.64
Time x Fire History	6	5.19	0.99	0.44	0.18	0.94	0.49
Time x Pod Treatment		2.95	0.56	0.76	0.26	1.38	0.20
Fire History x Pod Treatment	6	1.52	0.04	0.85	0.38	1.01	0.34
Site (Fire History x Pod Treatment)	1	37.41	7.16	0.001	0.38	2.00	0.001
Time x Fire History x Pod Treatment	20	3.26	0.62	0.71	0.13	0.69	0.66
Error	120	5.23			0.19		

There was strong evidence that Fire History (burnt vs unburnt sites) influenced the duration of independent visits made to sites by both prey (Pseudo- $F_{1,20} = 7.56$, $p(\text{perm}) = 0.01$; Fig. 11A, Table 7) and predators (Pseudo- $F_{1,20} = 3.72$, $p(\text{perm}) = 0.01$; Fig. 11B, Table 7). Prey visits were shorter at burnt compared to unburnt sites, while predator visits were longer (Fig. 11). Pod Treatment (present vs absent) did not affect the duration of prey visits (Pseudo- $F_{1,20} = 0.92$, $p(\text{perm}) = 0.36$). However, there was weak evidence (Pseudo- $F_{1,20} = 2.27$, $p(\text{perm}) = 0.08$) that predator visits were longer at burnt sites with pods. There was strong evidence that the duration of predator visits varied significantly between sites (Pseudo- $F_{20,120} = 1.59$, $p(\text{perm}) = 0.04$; Table 7), but there was no evidence site impacted prey (Pseudo- $F_{20,120} = 1.18$, $p(\text{perm}) = 0.28$; Table 7).

Prey visits were longer in period B (immediately after pod deployment) than at other times (Pseudo- $F_{6,120} = 2.77$, $p(\text{perm}) = 0.01$; Table 7), but this effect was the same at sites with and without pods (Pseudo- $F_{6,120} = 0.56$, $p(\text{perm}) = 0.74$), suggesting this was unrelated to pod presence.

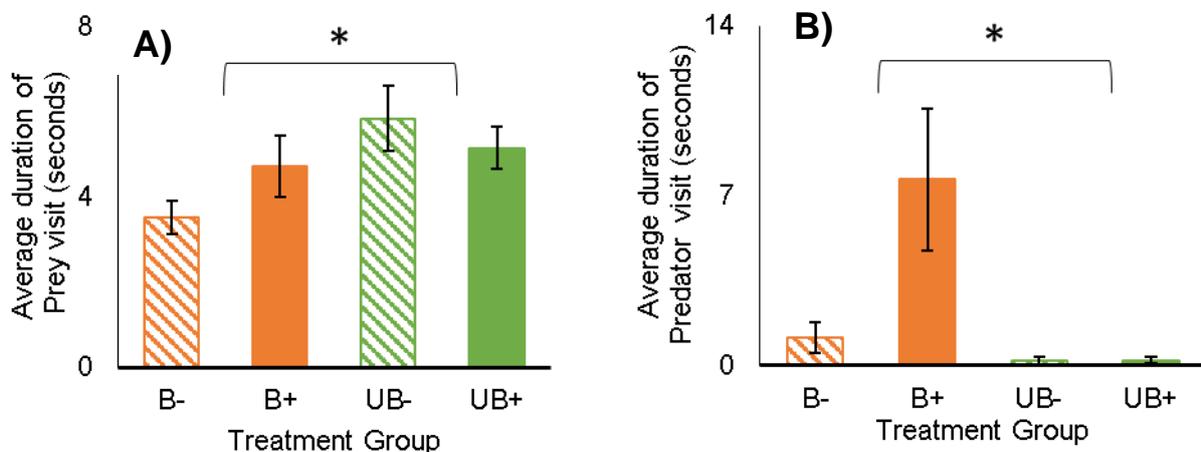


Fig. 11. Average (± 1 SE) duration of independent prey (A) and predator (B) visits to burnt (B) and unburnt sites (UB), with (+) and without (-) pods. Graphs represent averages across all sampling periods as there was no significant difference in the duration of visits across Time (Table 7). * Indicate significant difference between Burnt and Unburnt areas according to a Monte Carlo post-hoc test at $\alpha = 0.05$. $N = 6$ sites per treatment.

Table 7. Results of a univariate PERMANOVA analysis testing for sources of variation in the duration of site visits by prey and predators. Sites of varying Fire Histories (burnt vs unburnt), and Pod Treatment (present vs absent), were censused during 1 period before, and 6 after pod deployment at designated sites. Bold font denotes significant result at $\alpha = 0.05$.

Source	df	Prey			Predator		
		MS	pseudo-F	P(perm)	MS	pseudo-F	P(perm)
Fire History	1	125.17	7.56	0.01	736.25	3.72	0.01
Pod Treatment	1	15.17	0.92	0.36	449.65	2.27	0.08
Time	6	39.00	2.77	0.01	125.84	1.01	0.43
Fire History x Pod Treatment	1	15.17	0.92	0.36	446.35	2.26	0.10
Fire History x Time	6	21.37	1.52	0.18	125.26	1.01	0.44
Pod Treatment x Time	6	7.85	0.56	0.74	69.56	0.56	0.77
Site (Fire History x Pod Treatment)	20	16.55	1.18	0.28	197.68	1.59	0.04
Fire History x Pod Treatment x Time	6	7.85	0.56	0.74	62.73	0.51	0.83
Error	120	14.07			124.22		

Independent prey visits in which grooming, foraging or vigilant behaviours were displayed are shown in Fig. 12. There was little evidence that prey vigilance was affected by Fire History (Pseudo- $F_{1,20} = 2.82$, $p(\text{perm}) = 0.09$; Table 8), but it was very strongly influenced by site variation (Pseudo- $F_{20,120} = 3.65$, $p(\text{perm}) = 0.001$; Table 8). Grooming behaviour was moderately influenced by Fire History (Pseudo- $F_{1,20} = 5$, $p(\text{perm}) = 0.03$) and weakly affected by site (Pseudo- $F_{20,120} = 1.62$, $p(\text{perm}) = 0.06$). However, as there were limited grooming displays ($N = 4$) throughout the experiment, these results may not be robust . There is no evidence that any treatment or interaction influenced foraging behaviour.

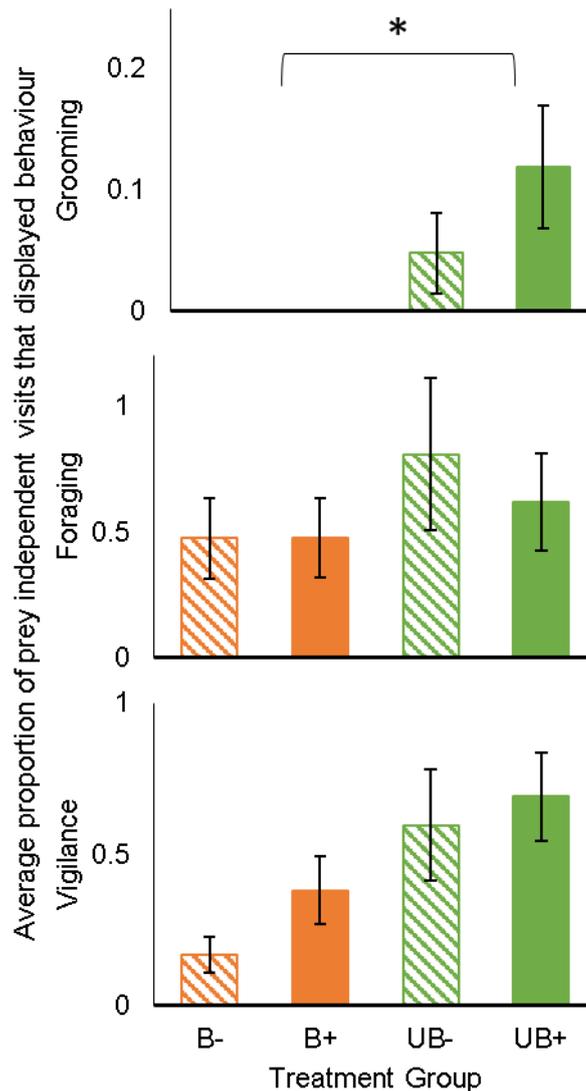


Fig. 12. Average (\pm SE) number of independent prey visits to burnt (B) and unburnt (UB) sites with (+) and without (-) pods in which grooming, foraging or vigilant behaviours were displayed. * Indicates significant difference according to univariate PERMANOVA at $\alpha = 0.05$. $N = 6$ sites per treatment.

Table 8. Results of a univariate PERMANOVA analysis testing for differences in the number of independent visits on which prey displayed foraging, grooming or vigilance behaviours at Sites of varying Fire History (burnt vs. unburnt), and Pod Treatment (present vs. absent), observed at two different Times: before and after pod deployment. Bold font denotes significant differences at $\alpha = 0.05$. Bold font denotes significant result at $\alpha = 0.05$.

Source	df	Foraging			Grooming			Vigilance		
		MS	Pseudo -F	P (perm)	MS	Pseudo -F	P (perm)	MS	Pseudo -F	P (perm)
Fire History	1	2.38	0.97	0.33	0.29	5	0.03	5.72	2.82	0.09
Pod Treatment	1	0.38	0.15	0.71	0.05	0.92	0.38	1.01	0.50	0.53
Time	6	0.65	0.35	0.91	0.04	1.15	0.34	0.69	1.25	0.28
Fire History x Pod Treatment	1	0.38	0.15	0.71	0.05	0.91	0.36	0.15	0.07	0.83
Fire History x Time	6	1.48	0.80	0.59	0.04	1.15	0.36	0.40	0.72	0.65
Pod Treatment x Time	6	2.53	1.37	0.21	0.03	0.71	0.64	0.91	1.64	0.14
Site (Fire History x Pod Treatment)	20	2.47	1.33	0.14	0.06	1.62	0.06	2.03	3.65	0.001
Fire History x Pod Treatment x Time	6	1.34	0.72	0.63	0.03	0.71	0.65	0.61	1.09	0.40
Error	120	1.85			0.04			0.56		

At burnt sites, predators showed more investigative and destructive behaviour at sites with pods than without (Fig. 13). Destructive and investigate behaviours were only displayed within the burnt environment (Fig. 13). There was very strong evidence that Fire History influenced investigative behaviour (Pseudo- $F_{1,20} = 8.23$, $p(\text{perm}) = 0.001$; Fig.13, Table 9).

There was weak evidence for destructive displays being influenced by Fire History (Pseudo- $F_{1,20} = 3.05$, $p(\text{perm}) = 0.06$; Fig. 13, Table 9), Pod treatment (Pseudo- $F_{1,20} = 3.05$, $p(\text{perm}) = 0.07$) and the interaction of Fire History and Pod Treatments (Pseudo- $F_{6,120} = 3.05$, $p(\text{perm}) = 0.06$). However, overall there were very few observations of these behaviours (Fig. 13, Table 9).

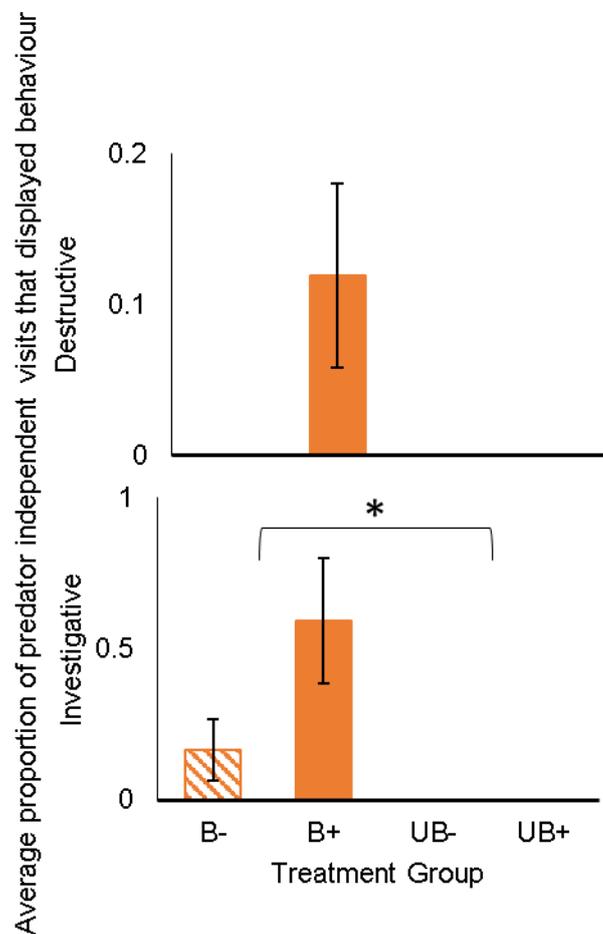


Fig. 13. Average (± 1 SE) number of independent predator visits to burnt (B) and unburnt (UB) sites, with (+) and without (-) pods in which investigative and destructive behaviour was displayed. * Indicates significant difference between Burnt and Unburnt area according to univariate PERMANOVA at $\alpha = 0.05$. N = 6 sites per treatment.

Table 9. Results of a univariate PERMANOVA analysis testing for sources of variation in the number of independent visits in which predators displayed destructive and investigative behaviours. Sites of varying Fire History (burnt vs. unburnt), and Pod Treatment (present vs. absent), observed at two different Times: before and after pod deployment. Bold font denotes significant result at $\alpha = 0.05$.

Source	df	Destructive			Investigative		
		MS	pseudo-F	P(perm)	MS	pseudo-F	P(perm)
Fire History	1	0.15	3.05	0.06	6.10	8.23	0.003
Pod							
Treatment	1	0.15	3.05	0.07	1.93	2.60	0.14
Time	6	0.02	0.59	0.75	0.72	1.30	0.25
Fire History x Pod							
Treatment	1	0.15	3.05	0.06	1.93	2.60	0.11
Fire History x Time	6	0.02	0.59	0.77	0.72	1.30	0.27
Pod Placement x Time	6	0.02	0.59	0.78	0.16	0.30	0.94
Site (Fire History x Pod Treatment)	20	0.05	1.21	0.19	0.74	1.34	0.13
Fire History x Pod Treatment x Time	6	0.02	0.59	0.77	0.16	0.30	0.95
Error	120	0.04			0.55		

Habitat Pods design assessment

Three families of small mammal were observed entering habitat pods: Dasyuridae, Muridae and Pseudocheiridae. By contrast, no predator species gained entry over the duration of the study. Of their total independent visits to sites with Habitat Pods, Dasyuridae, Muridae and Pseudocheiridae entered the internal area at least once during 47 %, 39 % and 9 % of their visits respectively (Fig. 14). There were five entrance choices available to the target animals: 100 mm, 60 mm, 40 mm, or 30 mm diameter circular entrances, or by squeezing underneath the structure. Across all entries by all family groups, the most favored entrance size was 100 mm (responsible for 46 % of all Habitat Pod entries), followed by 60 mm (33 % of all entries) (Fig.14).

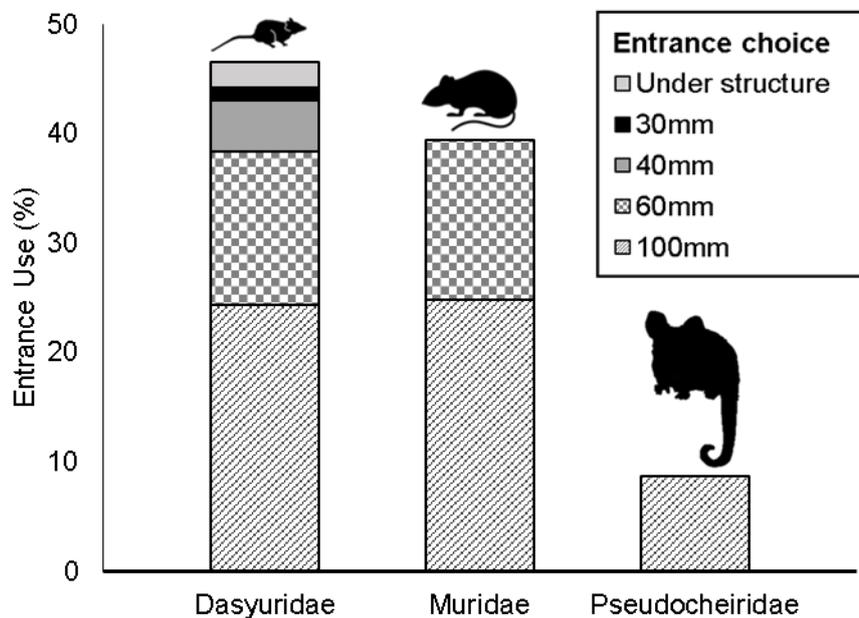


Fig. 14. The percentage of total independent visits in which different entries were used by each prey Family. Note that not all species observed in camera footage entered the pods.

Pods had a discernible effect on the microclimates measured by iButtons. Internal iButtons record the most stable microclimate (lowest range of temperatures), while Corridor iButtons recorded the most variable microclimate (broadest range of temperatures) (Pseudo- $F_{2,65} = 17.33$, $p(\text{perm}) = 0.001$; Fig.15, Table 10). This was largely due to hotter maximum temperatures along the corridors, and cooler maximum and warmer minimum temperatures within the pods. There was no significant difference in the average temperatures recorded by iButtons in each of the different locations (External, Corridor, Internal; Pseudo- $F_{2,65} = 1.46$, $p(\text{perm}) = 0.24$; Table 10). There was no evidence that these effects were dependent on Fire History (non-sig. Fire history x Microclimate interactions, Table 10).

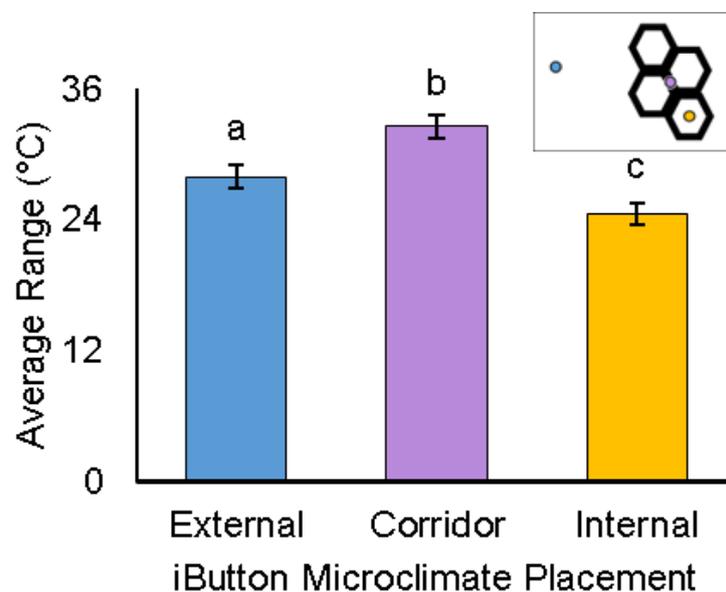


Fig. 15. The average range of temperatures experienced at different iButton microclimate placements (External, Corridor, Internal) across all sites with Pods (B+, UB+). Letters above bars represent the results of PERMANOVA post-hoc pair-wise test, bars with different letters are significantly different from one another at $\alpha = 0.05$.

Table 10. Results of a univariate PERMANOVA analysis testing for effects of Microclimate (Internal, Corridor, External) on the average and range in temperature (°C) recorded at burnt and unburnt sites (Fire History) with pods. Bold font denotes significant result at $\alpha = 0.05$. A PERMANOVA post-hoc pairwise test was performed on significant results to identify where key differences lay.

Source	df	Average temperature (°C)			Range (°C)		
		MS	pseudo-F	P(perm)	MS	pseudo-F	P(perm)
Fire History	1	1.37	0.93	0.36	0.89	0.03	0.87
Microclimate	2	2.15	1.46	0.24	450.53	17.33	0.001
Fire History x Microclimate	2	0.1	0.07	0.92	29.17	1.12	0.36
Error	65	1.47			26		

Neither the average nor the range of Relative Humidity (%RH) values recorded differed significantly among the Internal, Corridor, or External iButton locations (non-significant. Microclimate; Table 11).

Table 11. Results of a univariate PERMANOVA analyses testing for effects of Microclimate (Internal, Corridor or External) on average and range in relative humidity (%RH), at burnt and unburnt sites (Fire History) receiving pods. Bold font denotes a significant result at $\alpha = 0.05$.

Source	df	Average (RH%)			Range (RH%)		
		MS	pseudo-F	P(perm)	MS	pseudo-F	P(perm)
Microclimate	2	20.20	1.20	0.42	96.53	1.02	0.39
Error	9	18.41			94.99		

Although degradation was likely exacerbated by above-average rainfall, no Habitat Pod cluster had completely degraded (average Score of 5) by the completion of the 21-week experiment (Fig.16). Rates of pod degradation were similar between burnt and unburnt sites (Fig. 17).

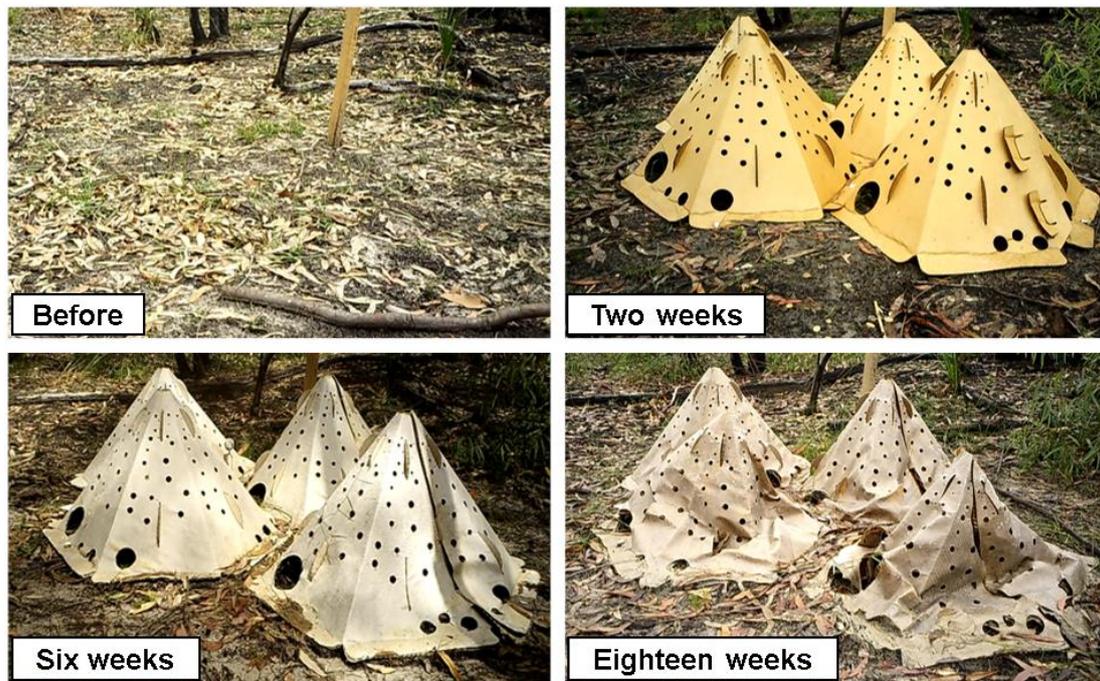


Fig. 16. Progression of Habitat Pod degradation at a burnt site. Before photo highlights lack of vegetative understory. At two weeks the cluster has not begun to degrade, with an average score of 1. After six weeks Pods showed early signs of water damage and surface peeling, with average degradation score of 2. By eighteen weeks internal structures were beginning to collapse but were still upright and the average degradation score of 4.

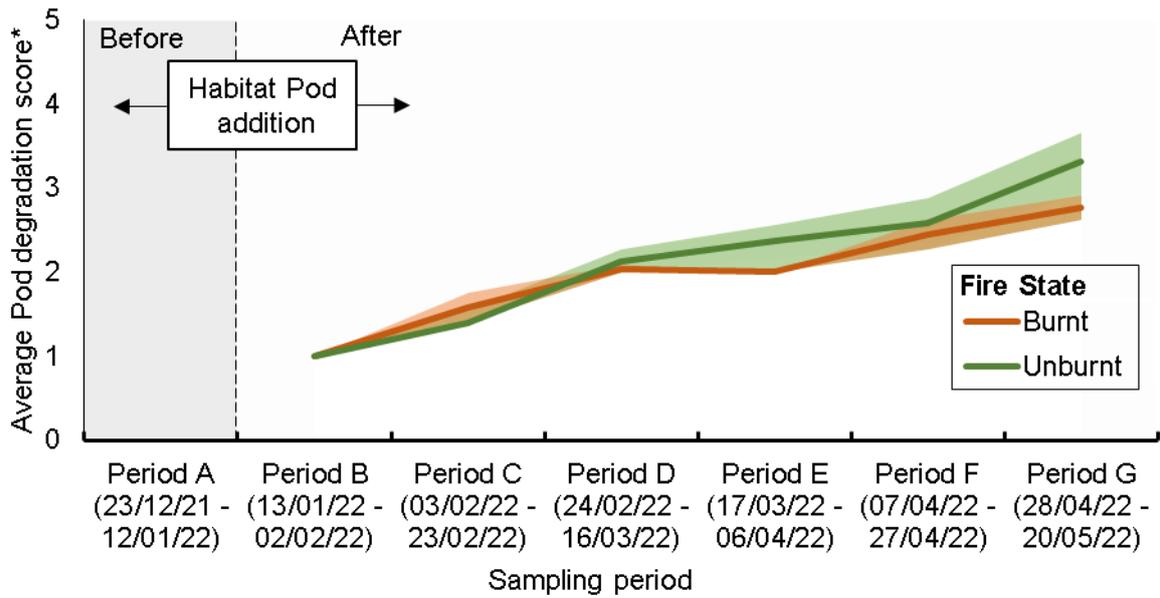


Fig. 17. Habitat Pod degradation through time. Score of 5 indicates Habitat Pod is entirely flat on ground, 1 indicates no degradation.

Discussion

This field trial compared natural refuge conditions within burnt and unburnt environments and investigated the use of Habitat Pods by small ground-dwelling mammals in these areas.

Ecological conditions within the burnt environment

It was anticipated that burnt environments would provide lower vegetation cover, fewer available refuges, and less stable temperatures for small mammals (Hypothesis 1). As expected, I recorded significantly less vegetation cover within the burnt environments, with no significant regeneration observed to occur throughout the project (Fig. 7).

However, other comparisons between the burnt and unburnt environments were less straightforward. Fires typically remove logs, and associated log-hides (Collins et al., 2012, Williams and Faunt, 1997), which are key resources for several of our target species (Hradsky et al., 2017, Johnstone et al., 2011, Sutherland and Dickman, 1999, Maitz and Dickman, 2001). Log counts within the study area were variable across all treatment groups, while log-hide counts were surprisingly higher within the B- treatment group (Fig. 8). This trend can be likely be attributed to spatial variation being poorly capture within our relatively small sampling area, as we only counted logs within the 10 x 10 m site areas (Fig. 6). It is recommended that future studies consider accounting for refuge availability at a broader spatial scale.

Typically, burnt areas have more varied thermal regimes due to decreased albedo and evapotranspiration (Beringer et al., 2003, Chambers and Chapin III, 2002). However, this project found only weak evidence of Fire History influencing ambient temperature range or averages between treatment groups (Table 5). This unexpected outcome may be partially attributed to continued rainfall and increased cloud cover reducing the impacts of albedo.

Fauna activity within the burnt environment

It was anticipated that prey would be less active in the burnt environment, due either to mortality or avoidance of the burn scar. By contrast, I expected that predator activity may be increased in the burnt area, if predators were attracted to the area (Hypothesis 2). The removal of understory vegetation has previously been associated with decreased prey foraging efficiency (Bleicher and Dickman, 2020, Brown and Kotler, 2004, Stawski et al.,

2015, Matthews et al., 2017) while also attracting predators into the area, presumably due to increased hunting opportunities (McGregor et al., 2016, McGregor et al., 2015).

This hypothesis was supported by strong evidence for increased predator activity, and weak evidence for decreased prey activity at burnt sites. Although several of the target species have been found to survive fire (Matthews et al., 2017, Stawski et al., 2015, Lindenmayer et al., 2005), a portion of the reduction in prey activity could be attributed to direct mortality from the fire (Banks et al., 2011). Also, while some of the target species do not typically migrate from burnt areas (Matthews et al., 2017, Stawski et al., 2015, MacGregor et al., 2013), some of this decline could be attributed to emigration from the area. On the whole, it is likely that decreased activity can be attributed to the well-documented decline of surviving individuals within the burnt environment (Lindenmayer et al., 2008a, Matthews et al., 2017, Penn et al., 2003, Friend, 1993, Hradsky et al., 2017).

The observed increase in Canidae and Felidae activity within burnt sites may be explained by predators benefitting from the reduced vegetation density of burnt environments (Fig.10). These invasive predators (foxes and cats) have been shown to travel long distances to hunt in burnt environments (McGregor et al., 2016, Hradsky et al., 2017). Several studies have recorded increases in localised predator density after a fire (Leahy et al., 2016, Hradsky et al., 2017, Green and Sanecki, 2006). It is interesting to note that *F. catus* was only recorded within the burnt environment (Fig. 9). Thus, my results are in agreement with the growing body of literature suggesting that invasive predator activity is increased in burnt environments.

I saw a similar pattern in the average duration of visits by predators and prey. Prey visits were shorter, on average, at burnt than unburnt sites, while predator visits showed the opposite pattern (Fig. 11). If prey perceive elevated predation risk in burnt environments, then they may shorten their bursts of activity to limit their exposure to this risk. Predators, on the other hand, may be moving through slowly to increase hunting opportunities (Sih, 1984, Brown, 1988, Stillman et al., 2000).

Fauna behaviour within the burnt environment

I expected prey to be more fearful at burnt sites, as these areas are associated with increased predator activity and decreased refuge availability (Hypothesis 3). Within mammal behavioural research, grooming and foraging are generally only expected where animals feel relatively relaxed. Vigilance, on the other hand, is used to scan for predation or other risks, and can be interpreted as indicative of perceived vulnerability or stress (Carthey and Banks, 2016, Brown, 1999, Griffin and Evans, 2003). Within this project, these behaviours indicated how fearful (vulnerable to predation) prey species felt, and how this was influenced by Fire History or Pod Treatment.

My results showed that prey groomed significantly less frequently in burnt environments. If grooming indicates relatively relaxed behaviour, then reduced grooming at burnt sites is consistent with the increased predator activity that I observed there (Fig.12). However, I did not find any differences in foraging behaviour across sites, perhaps reflecting the overall low incidence of this behaviour. Surprisingly, vigilance displays were detected more often from prey at unburnt, rather than burnt sites.

One possibility is that small mammals could see shorter distances within the more densely vegetated unburnt areas, and so felt the need for more frequent vigilance. However, this would contradict the large body of research suggesting that prey generally feel safer under cover (Loggins et al., 2019, While and McArthur, 2006).

Finally, increased vigilance behaviour could also be attributed to a higher density of stick runways (Douglass and Reinert, 1982, Bowman et al., 2000, Lindenmayer et al., 2003) within the unburnt environment. Although I did not directly measure this phenomenon, members of the *Dasyuridae*, *Burramyidae*, and *Muridae* commonly moved along sticks and branches (woody debris with a diameter <10 cm) visible within the camera frame. Momentary vigilance was often observed when individuals paused at the end of these runways, before jumping off onto the ground. As most small woody debris are removed by fire, it makes sense that this vigilance display occurred more frequently in unburnt environments.

Habitat Pod design assessment

Although Habitat Pods are not intended for long-term shelter, measurements of microclimate suggested that they provide a suitable thermal range and relative humidity for use by prey species, and that the internal area within the pods buffers outside temperatures. Additionally, the corridor maximum temperature was approximately 4.6°C higher on average than the external microclimate, which may benefit species that bask when resources are low, such as the yellow-footed antechinus (Matthews et al., 2017). Ectotherms, including reptiles within the Critical Weight Range, have also been shown to select basking sites that are positioned close to refuge or foraging areas (Lanham and Bull, 2004, Kerr et al., 2003, Shah et al., 2004). The warmer corridors, and their proximity to the internal shelters, may attract native animals that benefit from basking within burnt areas.

The entrances and internal structures of Habitat Pods were designed so that prey being pursued could enter quickly and exit abruptly from a range of directions, making the pursuer lose track of prey. Although I did not capture any predator pursuits on camera, analysis of footage confirmed that the entrances were appropriately sized for small mammals to enter and exit while still restricting predator access. No predators gained entrance to the internal structure of the pods during the study. Additionally, the semi-arboreal Burramyidae and Dasyuridae families were repeatedly observed using the 10 mm holes as grip points to climb the structures.

As anticipated, Habitat Pods progressively biodegraded within the natural environment. It was expected that these structures would take 12 months to completely decompose, although this figure is expected to vary depending on environmental conditions. Within this field trial, almost all structures remained standing after 21 weeks, despite heavy rainfall throughout the course of the project (Fig. 16, Fig. 17). This indicates that the structures are capable of lasting for prolonged periods within challenging burnt environments.

Additionally, within the only location that the structures had completely collapsed, *Perameles nasuta* (Long-nosed Bandicoot) were observed foraging within the collapsed remains of Habitat Pod. Bandicoots are known to be attracted to deep leaf litter, mulch, and compost, as these moist media attract high densities of their invertebrate prey. Thus, after providing short-term refuge for small mammals, the decomposition of Habitat Pods

may also provide habitat for invertebrates, and ultimately, additional foraging opportunities for insectivorous mammals.

Habitat Pods and prey

It was expected that adding Habitat Pods to the burnt and unburnt environment would reduce the size of any differences in predator and prey activity and behaviour (Hypothesis 4). Despite small mammals readily interacting with the refuges, there was no detectable influence on prey activity or behaviour at either burnt or unburnt environments.

The absence of an effect of pods on small mammals may reflect an insufficient density of pods deployed. As the first trial of Habitat Pods, this trial used a precautionary approach of deploying relatively few pods, at low density to limit any maladaptive effects. Habitat pods were designed to imitate the cover and refuge provided by natural understory vegetation. However, to facilitate movement of small mammals across home ranges that are typically in the order of 1Ha (Maitz and Dickman, 2001), greater densities and distribution over larger areas are likely needed. At the density provided in the present study (one site/1.5Ha), it is likely that Habitat Pods were only occasionally encountered as “novel objects” and did not influence an individual’s movement throughout the rest of their home range.

Secondly, the project did not commence until 10 weeks post-fire, with Habitat Pods not being deployed until 13 weeks after the event. Habitat Pods are intended to provide emergency refuge for animals within the burnt environment, to reduce immediate mortality from exposure and predation. It is possible that the vulnerable individuals targeted by this project had either emigrated or perished during the period between fire and Habitat Pod installation, which would have reduced our chances of detecting any effect of adding pods.

Finally, it is possible that Habitat Pods did not have a marked impact on prey activity because food availability, rather than refuge availability, was the limiting factor within these environments. However, I suspect that limited food availability would in fact have increased small mammal interactions with Habitat Pod, as the refuges were observed to attract invertebrates and I observed (but did not objectively measure) that the internal chambers were encouraging vegetation regeneration. It is worth noting that there were several instances of prey foraging from the decomposing refuges towards the end of the project, which may be an unexpected benefit of the structures being biodegradable.

The cardboard corridors created by the Habitat Pod grounding flaps may mimic the properties of sheltered stick runways within the natural environment. This was supported by momentary vigilance immediately before transitioning from corridors into the natural environment, which mirrors the prey behaviour before disembarking a natural stick runway (Fig. 12, Fig. 14). These corridors have the added benefit of largely obscuring prey from the eyeline of terrestrial predators. A leading artificial refuge research project for terrestrial small mammals within Australia currently uses wire tunnels to achieve a similar effect, with attendant positive responses from small mammals (Bleicher and Dickman, 2020). Prey interactions with the biodegradable Habitat Pods indicate that the design provides both an easy to enter enclosed multi-exit area for prey under duress, as well as a perceived safe runway for prey species moving through the landscape. In addition, as Habitat Pods are biodegradable (Fig. 16, Fig. 17) they do not have the logistical complications of permanent wire tunnels.

The interactions of prey species with the Habitat Pods indicate that the design of these artificial refuges may be able to support small mammal species within post-fire environments. However, it is likely that a broader spatial distribution, and a more immediate post-fire deployment may be needed for future studies to have a better chance of detecting any influence of Habitat Pods on prey activity and behaviour.

Habitat Pods and predators

Although the Habitat Pods were designed to exclude predators, it was unclear if the addition of artificial refuges would influence predator activity or behaviour (Hypothesis 4). Previous artificial projects have unfortunately created ecological traps for prey (Battin, 2004), by inadvertently luring predators to the area (Ebrahimi et al., 2012, Anderson et al., 2016, Patterson et al., 2016). The average duration of individual predator visits to sites was significantly longer when pods were present, but encouragingly, overall predator activity (number of independent visits) was no greater (Fig.10). Instead, it appeared that predators were not actively seeking out pods but rather pausing to investigate them when they encountered them. As Habitat Pods are biodegradable and designed as a transient refuge (average prey visit was < 7 seconds; Fig. 11), any deposited odour cues would likely rapidly disperse in the exposed environment. It is therefore unlikely that the pods harboured residual prey odour, which can attract predators. Future research could further investigate this possibility.

Nevertheless, there were four instances of *Vulpes vulpes* being investigative to the point of destructive. Destructive behaviour was displayed exclusively within burnt environments that had received Habitat Pods. This is not surprising as there was significantly less predator activity within the unburnt environment (Fig. 10) and sites without Habitat Pods provided less opportunities for destructive behaviour (Fig. 13). On one occasion, *V. vulpes* dragged a Habitat Pod 1m away from the cluster (out of frame, Fig. 5C). Predators being able to move these structures may endanger prey seeking shelter within them, so will require further investigation. However, as entrance sizes restricted predator access to the internal compartments, these structures will still provide transient refuge for prey species.

On the whole, this is an interesting behavioural observation, and begs the question as to whether foxes might regularly attempt to destroy or break into potential prey refuges (such as stick piles or debris) in burnt environments or otherwise. This possibility deserves further investigation.

Conclusion

This initial field test of Habitat Pods investigated the potential for these structures to support ground-dwelling small mammals within burnt environments. The refuge design and clustered arrangement provided suitable microclimates and entrances for target prey Families, all of which interacted with the structures. Unfortunately, likely due to low Habitat Pod density or delayed deployment, the structures did not significantly influence small mammal activity or behaviour. This project contributes to a growing body of literature demonstrating the need for wildlife support within Australia's post-fire environments. Although population-scale impacts will require further testing, this project indicates that Habitat Pods are suitable for emergency post-fire deployment.

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Appendix. A

Table 12: List of all primarily partially or completely ground-dwelling mammals within the Critical Weight Range (~35g – 5.5kg) that are likely to occur within Marramarra National Park.

Species in area:	Relevant attributes:
Muridae <i>Pseudomys gracilicaudata</i> , <i>Pseudomys novaehollandiae</i> , <i>Rattus lutreolus</i> , <i>Rattus fuscipes</i> , * <i>Rattus rattus</i> , * <i>Rattus norvegicus</i> , * <i>Mus musculus</i>	Diet: Plant material, fungi, insects (Friend, 1993, Watts and Braithwaite, 1978, Cockburn, 1980, Cheal, 1987, Carron et al., 1990) *Human food, grains, small vertebrates and birds eggs Approx. Home Range: Up to 1ha (<i>Rattus fuscipes</i>) (Maitz and Dickman, 2001)
Dasyuridae <i>Antechinus agilis</i> , <i>Antechinus flavipes</i> , <i>Antechinus stuartii</i> , <i>Antechinus swainsonii</i> , <i>Planigale maculate</i> , <i>Sminthopsis murina</i>	Diet: Plant material, insects, small vertebrates (Lunney et al., 2001, Goldingay, 2000, Dickman and Steeves, 2004, Friend, 1993) Approx. Home Range: Up to 5ha (<i>Antechinus stuartii</i> male) (Lazenby-Choen and Cockburn, 1991)
Peramelidae: <i>Perameles nasuta</i>	Diet: Plant material, insects, roots, fungi (Hall et al., 2016) Approx. Home Range: Up to 3.3ha (MacGregor et al., 2013)
Burramyidae: <i>Cercartetus nanus</i>	Diet: Nectar, pollen, insects and plant matter (Tulloch and Dickman, 2007). Approx. Home Range: Up to 19.5ha (male) (Law et al., 2013)
Pseudocheirus: <i>Pseudocheirus peregrinus</i>	Diet: Plant matter (Hall et al., 2016) Approx. Home Range: 50m ² (Smith et al., 2003, Lindenmayer et al., 2008b)

Appendix. B

Table.13 Specifications of all sites, created by spatial analysis.

Site	Aspect	Vegetation Community	Distance from (m)			
			Creek Line	Walking Track	Alternative Fire History	Private Residence
-UB1	North	Sydney Sandstone Ridgetop Woodland	102	68	99	1710
+UB1	North	Sydney Sandstone Ridgetop Woodland	71	87	91	1410
-UB2	North	Yellow Bloodwood Forest	40	78	92	1080
+UB2	North	Sydney Sandstone Gully Forest	286	85	387	989
+UB3	North	Dry Sandstone Ridgetop Woodland	104	91	422	1090
-UB3	South	Sydney Sandstone Ridgetop Woodland	62	83	458	945
-UB4	North	Sheltered Gully Forest	74	86	679	1059
+UB4	South	Yellow Bloodwood Forest	183	117	878	1073
-UB5	East	Sydney Sandstone Gully Forest	89	71	710	710
+UB5	South	Yellow Bloodwood Forest	161	68	281	390
+UB6	South	Red Bloodwood - Scribbly Gum Woodland	107	105	325	136
-UB6	South	Sydney Sandstone Ridgetop Woodland	104	144	564	201
+B1	North	Dry Sandstone Ridgetop Woodland	189	74	253	2177
+B2	North	Yellow Bloodwood Forest	20	90	320	1963
-B1	North	Sydney Sandstone Ridgetop Woodland	241	102	192	1738
-B2	South	Sydney Sandstone Ridgetop Woodland	152	84	116	1478
-B3	South	Sydney Sandstone Ridgetop Woodland	268	70	130	1183
+B3	North	Red Bloodwood - Scribbly Gum Woodland	265	83	280	1180
-B4	South	Red Bloodwood - Scribbly Gum Woodland	208	168	130	939
+B4	East	Sheltered Gully Forest	74	60	257	1037
+B5	North	Red Bloodwood - Scribbly Gum Woodland	161	172	349	1228
+B6	North	Sydney Sandstone Gully Forest	210	70	90	871
-B5	West	Sydney Sandstone Heath	174	74	77	1104
-B6	North	Sheltered Gully Forest	140	70	52	1085