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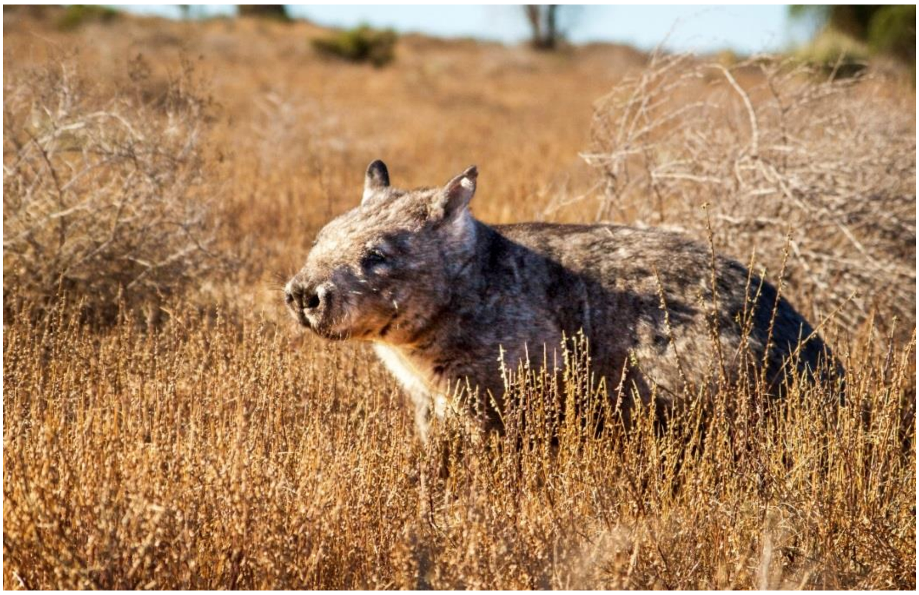
TRIAL REPORT: Establishing the effectiveness of a variety of non-lethal deterrents for southern hairy-nosed wombats.



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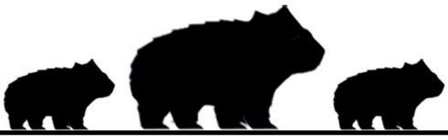

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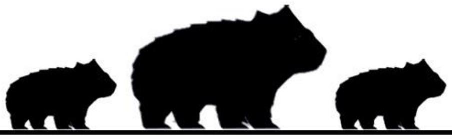

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1. Executive summary

The southern hairy-nosed wombat (*Lasiorhinus latifrons*) is one of the largest burrowing herbivorous mammals in the world. They construct large warren complexes with extensive tunnel systems, that often cause damage to infrastructure (e.g. roads, fences, and railways), pose safety risks for people, damage vehicles and heavy machinery, hinder agricultural production, resulting in thousands of dollars in damages (St John and Saunders 1989; Sparrow *et al.* 2011). Culling wombats, under a destruction permit system, is the main method used to reduce damages, but it is a very contentious and emotional issue for many stakeholders. Culling often fails to provide long-term relief from conflicts, with re-invasion of burrows being an ongoing problem (Stott 1998). Furthermore, the influence of culling on the long-term viability of this near threatened species is unknown. In order to improve the management of wombats, across the agricultural land on which they are predominantly distributed, cost-effective management strategies that balance the needs of wombats and farmers is vital.

The damage caused by wombat burrowing behaviour is of primary concern to landholders, who have identified the need to remove warrens from locations where they cause substantial damage (e.g. under infrastructure, or in the middle of cropping paddocks). As wombats are known to use multiple warrens within their home range, the opportunity exists to remove problem warrens and moderate their burrowing activity with minimal impact on the wombats. Currently, there are no guidelines or tools for the ethical removal of wombat warrens, and its effectiveness in reducing damage is unknown. This project aims to address this knowledge gap, by working with landholders to develop tools and methods to promote the sustainable management of wombats in the rangeland areas and establish the effectiveness of non-lethal interventions, to improve conservation outcomes, and enhance farm productivity. This will be achieved by evaluating ethical warren collapsing techniques, the success of warren collapsing in reducing damages, and the effectiveness of dog (*Canis lupus familiaris*) and dingo (*Canis lupus dingo*) odours in preventing the re-excavation of collapsed warrens.

Trials were conducted on three private properties within the rangelands. On each property, four small wombat warrens containing 1-5 burrow entrances, located in problem areas were identified in consultation with landholders. The warrens were monitored using remote cameras, for a two week control period. This provided a base line level of wombat activity prior to the destruction of burrows. Warrens were then gradually collapsed over a three day period. On day one, the first 1-2 metres of each burrow within the warren were collapsed, this was followed with the collapsing of another 1-2m of tunnel on the second day. Disturbing the burrows in this manner encouraged the wombats to leave. On the third day, the burrows were carefully excavated with a backhoe and filled in. The area was treated with either 200ml of dog urine, 200g of dingo faeces, or left as a control. Cameras monitored the collapsed warrens for up to six months post release, to determine if wombats re-excavated the warrens. Differences in the behaviour of the wombats before and after burrow collapse were compared using mixed effects models.

The gradual collapsing of wombat burrows over a three day period resulted in the evacuation of wombats from their burrows on 93% of occasions. Wombats failed to leave their partially collapsed burrows on two occasions, and a fourth day of excavation was required. On 59% of occasions, ripped warrens were re-excavated within a month of their collapse. The remaining 41% of warrens were not re-excavated for ≥ six months, and no new diggings were observed within 200m of the collapsed warren. The predator odour treatments of dog urine and dingo faeces did not significantly discourage wombats from recolonising the collapsed warrens. No difference was found in the number or duration of visits to the warrens before or after warren collapse, for either odour treatment. There was wide variation in responses within and between sites, suggesting there may have been other factors influencing the re-excavation of warrens. Due to the small sample size the causes for the success or failure of warren collapsing were unable to be determined.

To better direct management efforts and improve the success of warren collapsing a better understanding of the factors influencing the recolonisation of collapsed burrows is needed. Further research to increase the sample size, test other potential deterrents, and evaluate the impact of burrow collapsing on wombat ranging behaviour is recommended. Furthermore, evaluating the success of one-way gates positioned at burrow entrances together with the partial collapsing of warrens in managing the damage caused by warrens is recommended as a less costly and time intensive method of managing problem warrens.

2. Introduction

2.1 Human Wildlife conflicts

Human-wildlife conflicts (HWC) are becoming an issue of increasing concern in the 21st century, as growing human populations increasingly compete with wildlife for declining space and resources (Conover 2002; Woodroffe *et al.* 2005; Madden and McQuinn 2014). Human land use dominates over half of earth's land surface (Sanderson *et al.* 2002; Watson *et al.* 2016). Few human land uses have as great an impact on wildlife resources or as much contact with wildlife as agriculture. Agriculture is one of the largest terrestrial land uses on the planet, occupying ~ 40% of ice-free land (Ramankutty and Foley 1999; Foley *et al.* 2005). Biodiversity are increasingly being restricted to small fragmented patches within agricultural landscapes, increasing the potential for HWC. Conflicts involve a diverse range of species and encompass a wide range of problems that negatively affect millions of people and threaten a huge diversity of species worldwide, with varying degrees of severity.

The damage wildlife causes to farms ranges from nuisance behaviour, property damage, crop destruction, spread of disease, and stock losses. Damages can have severe economic impacts, affecting the viability of farms and increasing food costs for consumers (Conover 1997; Naughton-Treves and Treves 2005). Predation, harassment, and mauling of livestock by wild dogs (dingoes, domestic dogs, and their hybrids) is estimated to cause $66.3 million in damages to the Australian economy each year (Wild dog damage 2017). The burden of damage management typically falls on private landowners. Many landholders respond to wildlife damage with retaliatory killing. However, there is growing antipathy towards the use of lethal controls to resolve wildlife damage, due to conservation and ethical concerns (Craven *et al.* 1998; Madden 2004; Bradley *et al.* 2005). Increasingly, non-lethal alternatives like the use of deterrents, habitat manipulation, and translocation of problem animals are being proposed, but they have been met with mixed success (Craven *et al.* 1998; Baker *et al.* 2005; Ward *et al.* 2016).

Conversion of land for agricultural purposes is one of the chief drivers of habitat loss and degradation (Ramankutty and Foley 1999; Watson *et al.* 2016). Many ecosystems and biomes have fallen to food production (Hoekstra *et al.* 2005). Over sixty percent of threatened or near threatened species on the IUCN Red List are affected by agriculture (Maxwell *et al.* 2016). If the global trend in human population growth continues 9.8 billion people are expected to inhabit the earth by 2050 (United Nations Department of Economics and Social Affairs

Population Division 2017). To meet the rise in global food demand, agricultural production will need to increase by 60 - 100%, requiring an area larger than the size of Africa (Tilman *et al.* 2011; Alexandratos and Bruinsma 2012). Given this increasing demand for resources, and access to land, it is clear that HWC will not be eradicated in the near future. Conflict resolution between development and conservation will become increasingly important to foster environmental and production sustainability, and maximise wildlife and human well-being.

2.2 The southern hairy-nosed wombat

Southern hairy-nosed wombats (*Lasiorhinus latifrons*) are an iconic native Australian mammal; but they are also considered a pest throughout much of the agricultural land on which they are largely distributed. Wombats occur predominantly throughout South Australia and serve as the states faunal emblem. Consequently, great importance is placed on their survival and wellbeing from a political and social viewpoint. Recent research suggests the future of this near threatened species is not assured, with concerns over the impact of climate change, sarcoptic mange, and conflicts with the agricultural sector (Woinarski and Burbidge 2016). Conflicts between wombats and the agricultural sector have been ongoing for decades, and arise as a result of competition for resources. Wombats burrowing and grazing habits negatively affect agricultural productivity, while land clearance, overgrazing and the introduction of weed species negatively affect wombats (St John and Saunders 1989; Stott 1998; Sparrow *et al.* 2011; Woolford *et al.* 2014). Landholders often resort to retaliatory killing to alleviate the damage wombat's cause to agricultural properties; however, it is often ineffective and causes concern over the long-term survival of this species. Given wombats are predominantly distributed across agricultural land, developing non-lethal damage mitigation strategies to allow wombats and agriculturalists to co-exist will be critical to ensuring the long-term conservation of this species.

2.2.1 Species distribution

Prior to European settlement, the distribution of wombats was thought to be continuous, extending from the Murraylands in the east, through to south eastern Western Australia (St John and Saunders 1989). A lack of historical records makes this difficult to confirm (Aitken 1971). Recent research based on grey literature suggests that at the time of settlement their range was separated into two main populations on either side of Spencer Gulf (Swinbourne *et al.* 2017). Following European settlement in Australia, large-scale land clearance for agriculture, urban development, and the introduction of European rabbits (*Oryctolagus* *cuniculus*) are thought to have played a significant role in the range contractions of wombats (Aitken 1971; Temby 1998; McIlroy 2008). Currently, there are five distinct mainland populations, located on the Nullarbor Plain, Gawler Ranges, Eyre Peninsula, Yorke Peninsula, and the Murraylands (Figure 1). Within all of these populations, wombats are predominantly distributed across agricultural land. (St John and Saunders 1989; Alpers *et al.* 1998). There is also an introduced population on Wedge Island in the Spencer Gulf (St John and Saunders 1989). As wombats can spend considerable periods of time below ground and use multiple warrens (Finlayson, Shimmin *et al.* 2005), obtaining accurate estimates of wombat abundance is difficult. The last distribution wide survey of wombat abundance, conducted in 1985, estimated population sizes ranging from one hundred thousand animals on the Nullarbor, to a few hundred on the Yorke Peninsula (St John and Saunders 1989; Sparrow 2009). As a whole, the species is classified as near threatened (Woinarski and Burbidge 2016), only the Nullarbor population is considered secure, while the highly fragmented Yorke Peninsula population is considered endangered (St John and Saunders 1989; Walker 2004; Sparrow 2009).

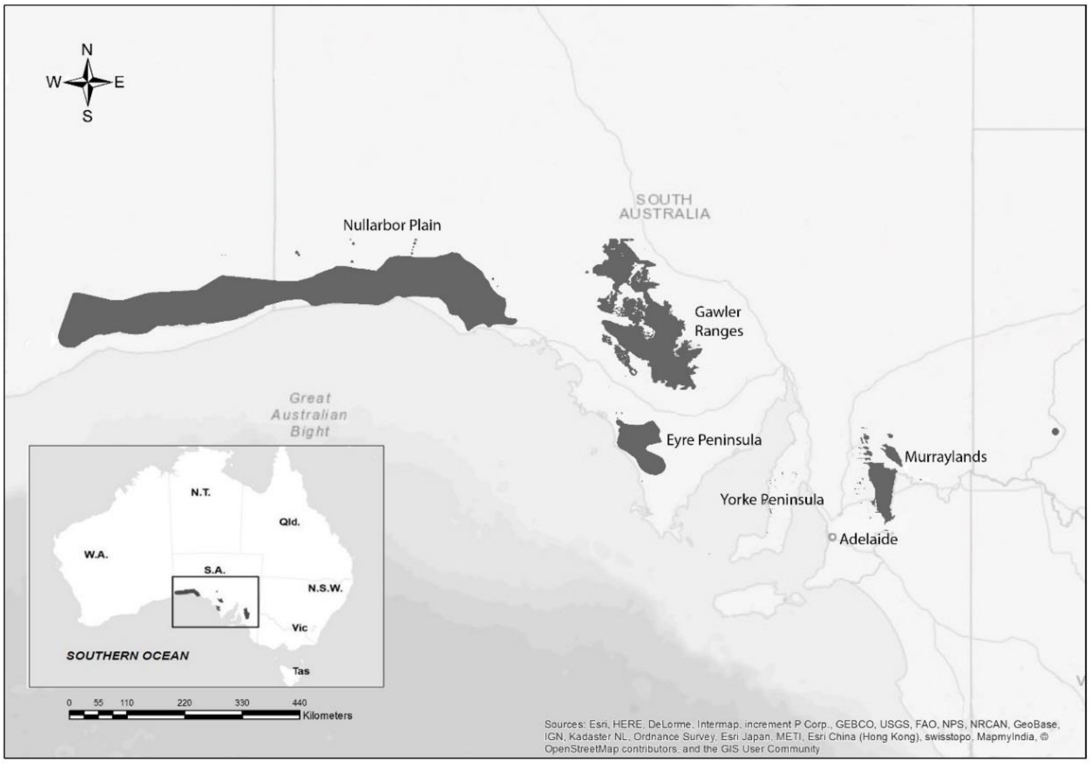

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Figure 1. The distribution of southern hairy-nosed wombats in Australia.

2.2.2 Home range and burrowing behaviour

Wombats are primarily nocturnal, sedentary animals. They have small home ranges for an animal of their size (approximately 4 ha), and there is little differentiation in home range size between sexes (Finlayson *et al.* 2005). Wombat home ranges are centred around their warrens, and they may use up to 10 warrens within their home range (Finlayson *et al.* 2005). The home ranges of individuals overlap substantially, with several individuals sharing warrens, but they rarely share burrows. Warrens can vary in size from 1 - 80 burrow entrances, with extensive tunnel networks that can cover areas in excess of 3000 square metres (Finlayson, Shimmin *et al.* 2005; Shimmin, Skinner *et al.* 2002). Burrows can vary in depth from 0.6 – 4.5 metres, depending upon soil type. Uniquely adapted to life in a burrow, wombats spend ~ 75% of their time below ground, relying heavily on their burrows for energy and water conservation, and protection from potential predators (Finlayson *et al.* 2010). Burrows provide wombats with a stable microenvironment, with temperatures ranging between 15-25°C, allowing them to survive in harsh climatic conditions (Shimmin *et al.* 2002). They emerge earlier and are active for longer during the cooler months of the year, preferring ambient temperatures of between 6°C and 18°C (Finlayson *et al.* 2005).

2.2.3 Breeding

Southern Hairy-nosed wombats breed seasonally, between July – December of each year. The length of the breeding season may vary from year to year depending upon environmental conditions. In drought years, reproduction may cease altogether (Finlayson, Taggart *et al.* 2007). Most young are born between mid-August and October, after a gestation period of 22 days (Wells 1989; Taggart and Temple-Smith 2008). Wombats have a slow reproductive rate, only producing a single young at a time, and on average two young every three years (Gaughwin *et al.* 1998; Finlayson *et al.* 2007; Taggart and Temple-Smith 2008). Joeys leave the pouch within 8-9 months, and weaning occurs at 12 months of age (Taggart *et al.* 2007). Young reach sexual maturity at three years of age, and during this period are highly vulnerable to the effects of drought (Taggart and Temple-Smith 2008). An increase in the adult population requires a minimum of 3 consecutive years of average or above average rainfall and associated pasture growth. Adult animals are known to reach more than 18 years of age in the wild and >30 years of age in captivity (Taggart and Temple-Smith 2008).

2.2.4 Human-wombat conflict

Conflicts between wombats and agriculturalists have been ongoing since the commencement of farming throughout the species range, negatively affecting both parties. All wombat populations experience some form of conflict with the human land use (St John and Saunders 1989; Sparrow *et al.* 2011)). Large-scale land clearance, competition from livestock, overgrazing, and the introduction of rabbits have contributed to the range contraction of wombats (Wells 1995; Swinbourne *et al.* 2017). The destruction and fumigation of wombat warrens, in a bid to control rabbits sheltering in them, contributed significantly to their decline (Swinbourne *et al.* 2017). In some regions, a loss of native grass species has led to a dietary shift towards introduced weed species that are high in toxins, severely affecting wombat health (Woolford *et al.* 2014). While some populations are declining, there have been reports of wombats expanding into new, previously uninhabited regions, escalating conflicts between rural landholders and wombats (Taggart *et al.* 2008).

Landholder's problems with wombats stem primarily from their grazing and burrowing habits (St John and Saunders 1989; Stott 1998; Sparrow *et al.* 2011). Wombats are perceived to provide grazing competition for stock and consume crops due to the large grazing halos evident around their warrens (Loffler and Margules 1980; St John and Saunders 1989; Stott 1998). As one of the largest burrowing herbivores in the world wombats create warren complexes, which vary in size from single entrance burrows to large warren systems with up to 80 burrows, which can span up to 3000 square metres (Loffler and Margules 1980; Shimmin *et al.* 2002; Triggs 2009). Warrens undermine infrastructure, such as roads, dams, fences, water tanks, windmills, and gravesites, causing damage and safety concerns (St John and Saunders 1989; Stott 1998). Fence destruction can result in escaping sheep, or the intrusion of predators such as wild dogs. Tank collapse leads to a loss of water for stock. Burrows under roads or in cropping paddocks pose safety risks to humans, when tunnels collapse and vehicles or heavy machinery fall through, this can result in a loss of time while vehicles are repaired and a reduction in crop quality if harvesting has to be delayed (St John and Saunders 1989; Stott 1998). Many agricultural properties are very large, and isolated, therefore maintenance and regular monitoring are difficult and time-consuming. Landholders estimate the damage caused by wombats to cost on average ≥ $10,000 per annum and in extreme cases, as much as $100,000 per annum (Sparrow *et al.* 2011). However, much of the damage that wombats cause or are perceived to cause is yet to be quantified.

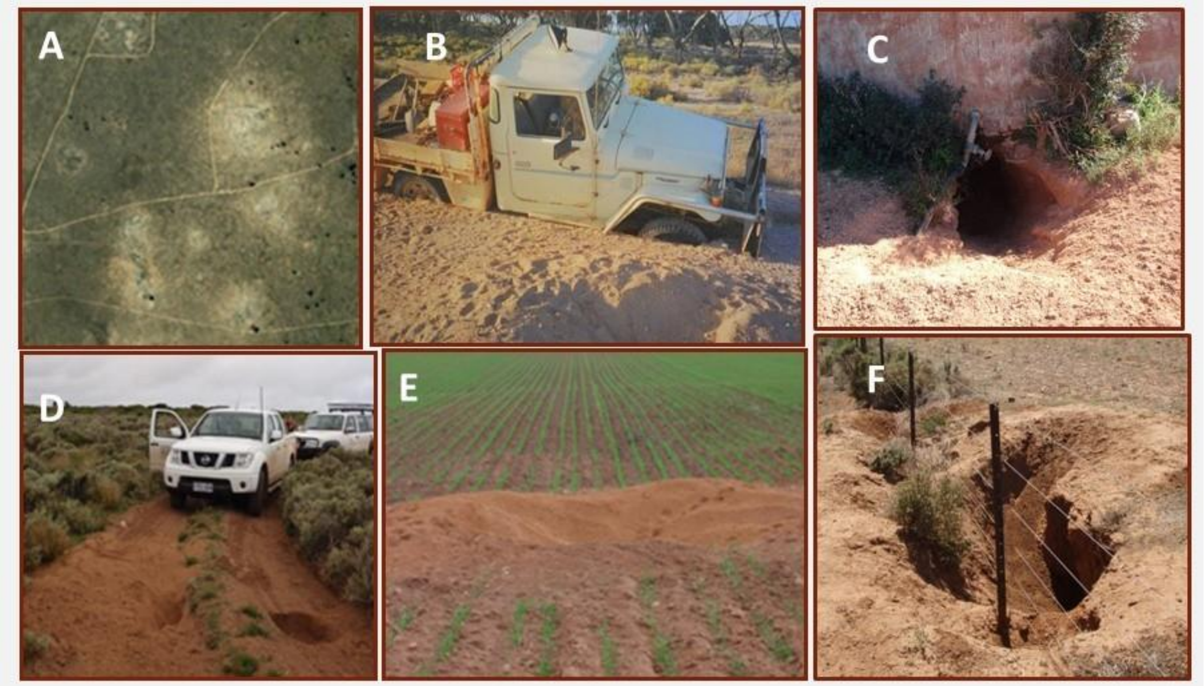

Figure 2. Examples of the damage wombats can cause to agricultural properties. A) The grazing halos produced around wombat warrens, visible from google earth. B) A ute that was fallen into a wombat burrow which collapsed under its weight. C) A wombat burrow under a water tank. D) A wombat burrow in the middle of a road. E) A wombat burrow in the middle of a cropping paddock and F) a wombat burrow undermining a fence.

2.2.5 Conservation & management

The management of wombats is a highly contentious issue. Problems arise when trying to strike a balance between the competing interests of farmers, conservationists, the general public, and the needs of the species. Though the southern hairy-nosed wombat is a protected species under state and federal legislation, destruction permits can be issued by the Department of Environment Water and Natural Resources in circumstances where wombats cause damage or threaten human safety (*section 53.1c of the SA National Parks and Wildlife Act 1972*). Due to a lack of scientific data, current permit allocations are not based on evidence or knowledge of the species, making the permit system ineffective for wombat conservation and management (Taggart *et al.* 2008). Many landholders are dissatisfied with the permit system and feel they are rarely allowed to destroy a realistic number of animals to mitigate damage, with recolonisation of burrows being an ongoing problem (St John and Saunders 1989; Stott 1998; Taggart *et al.* 2008). Subsequently, many landholders resort to culling outside of the permit system, resulting in inadequate data on the numbers of wombats culled and the intensity of conflicts.

Conservationists and animal welfare groups, on the other hand are concerned about the impacts of culling on the long-term survival of wombats, particularly in the face of mounting pressures such as climate change and disease. Altered pasture composition and/or below average rainfall can lead to high infant mortality and dwindling population numbers, especially where wombats must compete with domestic stock and other introduced herbivores. Sporadic outbreaks of sarcoptic mange can reduce animal numbers and threaten small isolated populations. There is mounting pressure to ban culling and implement non-lethal conflict mitigation measures.

Very few non-lethal management techniques have been trialled to assist in promoting co-existence between wombats and the agricultural industry. Electric fencing has been found to reduce wombat damage to the dog proof fence on the Nullarbor (St John and Saunders 1989), but it is not cost effective on a small landholder scale. Effective, socially acceptable, and economically viable management options are not yet available for this species. Quantified research on the extent and impact of conflicts and the effectiveness of non-lethal conflict mitigation measures are required to guide management decisions and develop a successful co-existence strategy that balances the needs of wombats and landholders.

The removal of warrens from problem locations such as the middle of cropping paddocks or under infrastructure may serve as a means of reducing conflicts between wombats and the agricultural sector. As wombats are known to use multiple warrens within their home range, the opportunity exists to remove problem warrens and moderate their burrowing activity with minimal impact on the wombats. Sett destruction has been successful in reducing the damage caused by badgers (*Meles meles*) in 62% of cases (Ward 2007). Currently, there are no guidelines or tools for the ethical removal of wombat warrens, and the effectiveness of such action in reducing damage is unknown. The recolonisation of collapsed warrens may be an ongoing problem. Deterrents may serve as a means of prolonging the time taken for wombats to recolonise vacant burrows. Predator odours have been found to act as deterrents for many other species (Nolte *et al.* 1994; Apfelbach *et al.* 2005). Rabbits avoid warrens treated with synthetically derived lion (*Panthera leo*) faeces for up to five months (Boag and Mlotkiewicz 1994), while bank voles (*Microtus oeconomus*) reduce their home range in response to the odours of weasel (*Mustela nivalis*) (Borowski 1998). Preliminarily evidence suggests wombats may respond to predator odours with altered space use (Descovich *et al.* 2012). A pilot study, conducted on the Far West Coast of South Australia examined the influence of warren destruction and dingo scents on the behaviour of wombats (Sparrow et al, 2016). Of the ten single entrance wombat burrows collapsed, those treated with domestic dog (n = 1), dingo carcass (n = 1), and the control (n = 3) had fresh diggings to new burrows within 20 days post-treatment. In contrast, the sites treated with dingo urine (n = 3) and faeces (n = 2) showed minimal signs of wombat activity (an occasional scratching) up to 75 days post-treatment.

2.3 Project aims

This project aims to develop tools and methods to promote the sustainable management of wombats in rangeland areas and to establish the effectiveness of non-lethal interventions, including:

- Evaluating the effectiveness of warren collapsing techniques, and their ability to reduce the damage caused by wombat digging behaviour.
- Assess the effectiveness of dog and dingo odours in reducing the damage caused by wombat burrowing behaviour.
- Work with landholders to resolve wombat management problems and promote co-existence with wildlife.

This research has the potential to provide an alternative option for landholders in the management of this species and promote DEWNR’s living with Wildlife philosophy by working with landholders in the Murraylands region. The effectiveness of burrow collapsing and deterrents will be assessed based on the time and costs of implementing these measures, as well as their effectiveness in preventing the recolonisation of collapsed burrows.

3. Methods

3.1 Study sites

This study was conducted on three agricultural properties in the Murraylands of South Australia, which had reported problems with wombats (Figure 3). The property in Sutherland, located approximately 12km northeast of Eudunda consisted of a mixture of cropping and grazing paddocks, interspersed with patches of remnant mallee scrub. Wombats were causing damage to fencing and digging in the middle of cropping paddocks on this property. The landholder employed a shooter to control the wombat population; however, conflicts were ongoing. The property in Black Hill, located 22km northeast of Cambrai was predominantly used for cropping, and bordered by a large patch of remnant mallee scrub. The landholder had experienced problems with wombats burrowing in the middle of paddocks for the last twenty years. The cropping paddock where the trials were conducted was so over run with wombat burrows the landholder had given up controlling them and no longer grew crops due to safety concerns. The third site, located 30 km south of Morgan is a pastoral property. It has been owned by the same family for the past 40 years. Wombats have only been present on the property for last 10 years, and their numbers have been increasing. The landowner is concerned over the damage their burrows are causing, and about grazing competition with livestock.

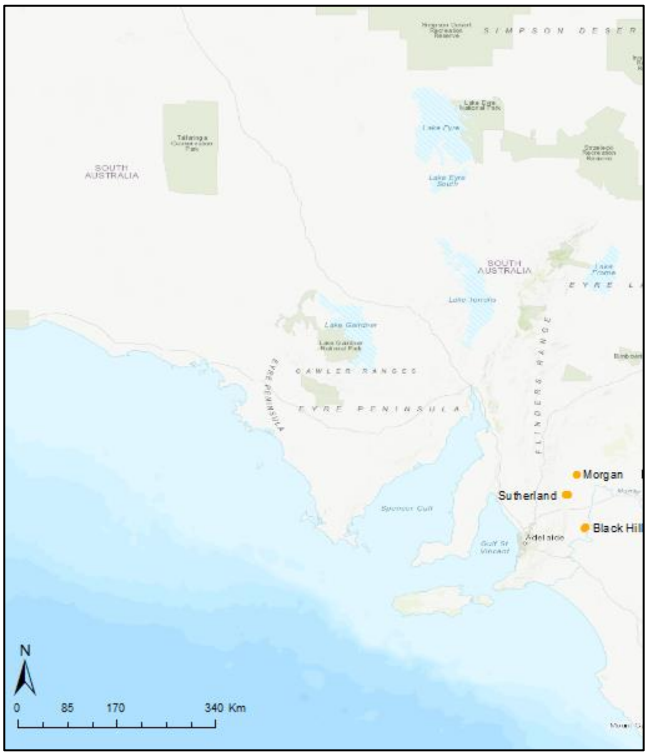

Figure 3. The locations of the three study sites, Sutherland, Black hill, and Morgan in South Australia.

3.2 Experimental design

Within each study site, four small warrens containing 1-5 burrow entrances were selected for the trials. Warrens were located in problem areas, such as the middle of cropping paddocks and selected based on the availability of alternative habitat. The selected warrens were >200m apart to ensure only one warren within an animal's home range was collapsed. As wombats can use up to 10 warrens within their home range, this ensured the availability of alternative burrows nearby, thereby minimising stress to the animals. Motion sensor cameras monitored wombat activity and behaviour in the warrens for two weeks, prior to their collapse. The collapsing of warrens took place over a three day period. On the first day, the first 1-2 metres of the burrows were collapsed using shovels and crowbars. A clear exit point was left for the wombats to escape (Figure 4). On day two, another few metres of the burrows were collapsed. The disturbance to the burrows over the first two days prompted the resident wombats to leave (Pers. coms. E. Sparrow). On the third day, a backhoe was used to excavate the rest of the burrows in their entirety. Every metre or so excavation work stopped to check the tunnel direction, and ensure no animals were present before continuing to dig. Following excavation, the area was levelled using the backhoe and one of three treatments was applied to the soil. Treatments consisted of either 200ml of dog urine, 200g of dingo faeces, or no treatment ie. a control site. The collapsed area continued to be monitored with cameras for 1-3 months and site visits were conducted regularly to determine if the warrens were re-excavated. Dog urine was collected from male domestic dogs, fed a meat-based diet. Dingo faeces was collected fresh from Cleland and Urimbirra Wildlife Parks in South Australia. All voids were frozen at -4^{0}C until use, as a fresh supply could not be maintained due to the large volume of voids required, and the effectiveness of odours are known to diminish with age (Bytheway *et al.* 2013; Hegab *et al.* 2014). Freezing samples may affect the stability of chemical messages contaiined within voids (Schultz *et al.* 2000), however, they have been found to elicit avoidance responses in rodents (Hayes *et al.* 2006; Russell and Banks 2007).

Figure 4. The process of burrow collapsing, A) Day one, the first metre of tunnel collapsed, B &C) Day three, ripping the entire warren with a backhoe, continually stopping to check the length and direction of tunnel and ensure no wombats were present, and D) A collapsed warren.

3.3 Photo analyses

Due to the volume of photos acquired, a subset of the data, totalling twenty consecutive nights, ten in each trial phase (before and after treatment application) were analysed. Nights constituted a 24hr period, beginning and ending at 6 am, due to the nocturnal behaviour of *Wombat*. For each night of the trial, the number and duration (s) of visits made to the burrow were recorded. Visits were considered the same if consecutive photos were ≤ 15s apart unless the *Wombat* was identified as a different individual. Animals were classified into adult or juvenile (1/4 size of an adult) age classes, to account for individual variations in responses. The proportion of time wombats spent in 7 main behaviours (Table 1) was recorded during each visit, as they are known to change when species react to threats (Apfelbach *et al.* 2005). Behaviours were analysed in one-second intervals, as vigilance in common wombats (*Vombatus ursinus*) has been observed to last for as little as 1 second (Favreau *et al.* 2009). To distinguish treatment effects from natural temporal fluctuations in *Wombat* behaviour, moon phase, nightly rainfall, and minimum overnight temperature, were extracted from the Australian Bureau of Meteorology’s nearest weather stations.

Table 1. The classifications of wombat behaviours, modified from Descovich *et al.* (2012).

Behaviour	Classification
Vigilant	Sitting, lying, or standing with head up in alert position or scanning of head
Resting	Sitting, lying, or standing, awake and relaxing, scratching, rubbing or rolling
Travelling	Walking or running at a constant gait without stopping
Exploratory	Sniffing the ground or air
Digging	Digging/scratching at dirt
Unknown	Behaviour unable to be discerned, wombats not in full view

3.4 Statistical analyses

Linear mixed effects models (LMM), generalised linear mixed effects models (GLMMs) and mixed-effects beta regressions were used to investigate *Wombat* responses to warren collapse, and the application of treatments. Visits by juvenile *Wombat* were excluded from analysis, due to insufficient data. All analysis was conducted in *R-3.3.1* (R Core Team 2014).

3.4.1 Recolonisation

The time taken for wombats to re-establish collapsed warrens was analysed using LMM in the *lme4* package (Bates *et al.* 2015). Treatment, warren complexity (blind tunnel, branching tunnel, or complex interlinked tunnels), distance to the nearest warren, and the number of wombats using the warrens were fitted as fixed effects. Site was fitted as a random effect in all models. Models were evaluated using Akaike's Information Criterion (AIC), Akaike weights (*wi*), and behaviour of model residuals. Post hoc comparisons of differences in the time taken for wombats to recolonise burrows between the control and odour treatments were conducted using planned comparisons of means for the model of best fit, in the *multcomp* package (Hothorn *et al.* 2008).

3.4.2 Visit duration

Differences in the duration of visits to burrows before and after warren collapse and treatment application were analysed using LMM in the *lme4* package (Bates *et al.* 2015). The response variable, duration of visits was log transformed to meet the assumptions of normality. All models were fit with the fixed interaction between the explanatory variables treatment by trial phase. Warren by site, night, and warren by site by night interactions were fitted as random effects in all models, to account for repeated observations within warrens and sites across multiple nights. Time (night of the trial phase (1-10)) was fitted as an interaction with treatment by trial phase, to determine if wombats habituated to the treatments. In addition, the weather parameters of rainfall, moon phase and minimum overnight temperature, were fitted as fixed factors. Models were evaluated using Akaike's Information Criterion (AIC), Akaike weights (*wi*), and behaviour of model residuals. Post-hoc differences between the trial phases (before and after treatment application) for each treatment were assessed using planned comparisons of means for the model of best fit, using the *multcomp* package (Hothorn *et al.* 2008).

3.4.3 Number of visits

Differences in the number of visits made to burrows before and after treatment application were analysed using GLMMs in the *lme4* package (Bates *et al.* 2015). Preliminary analysis with Poisson models revealed overdispersion, so models were re-fitted using a negative binomial distribution, with an additional parameter to represent overdispersion. All models included the explanatory variable of treatment by trial phase and the random intercept interaction of warren by site, to account for repeated measures within warrens and sites. Additional models included the fixed factors of rainfall, minimum overnight temperature, and moon phase. Model selection and post-hoc comparisons were conducted using the same approach described for the analysis of visit duration.

3.4.4 Behaviours

Six behaviours were observed throughout the trials (Table 1). The effects of treatments on the proportion of time wombats spent in each behaviour were analysed using mixed-effects beta regression models in the *glmmADMB* package (Fournier *et al.* 2012). Each model contained the fixed interaction of treatment by trial phase, and the random interaction effect of warren by site, to account for repeated measures within warrens and sites. To determine if *Wombat* became less wary of the treatments, time (1-5) was fitted as an interaction with treatment by trial phase. Additional models included the fixed factors of minimum overnight temperature, rainfall, and moon phase. Model selection and post-hoc comparisons were fit using the same approach described for the visit duration analysis.

4. Results

Over the course of the trials, four warrens were monitored at each of the three sites, totalling 12 warrens, containing 28 burrows. Four warrens were treated with dog urine, four with dingo faeces, and four were controls. Throughout the study, 44,487 photos of wombats were collected and 907 visits of ≥ 3s in duration were made to the warrens by adult wombats.

4.1.1 Burrow collapsing

The warrens varied in structure from blind single entrance burrows, branching single or multiple entrance burrows, to multiple entrance branching interconnected burrows. Tunnel length varied from between 3 - 18 m and the depth ranged between 1 - 4 m. The complexity of the burrows was unable to be determined until they were collapsed. The time taken to collapse the warrens varied greatly, from 1½ - 8 hours and was dependent on warren complexity. In 93.5% of cases, gradual collapsing resulted in the evacuation of wombats from their burrows. On two occasions, wombats remained within their burrows following the gradual collapsing of burrows over three days. In these instances, the tunnels were excavated up to the point where the wombat was present and left open for a fourth day to encourage them to leave. One wombat did not exit the burrow after four days of collapse and had further excavated the tunnel by 8m. This wombat was safely removed from the burrow and subsequently made its way to an alternative warren. The collapsing of small wombat warrens of 1-5 burrow entrances is estimated to costs between $600 – 1,500, but costs may vary substantially based upon the expanse of underground tunnel networks and access to machinery.

4.1.2 Recolonisation

There was wide variation in the time taken for wombats to recolonise burrows, across treatments and sites. At Sutherland, the control warren and the two warrens treated with dingo faeces were recolonised within 1-3weeks of collapse. The warren treated with dingo urine has not been recolonised, some six months later. No warrens at Black Hill have been recolonised for six months, regardless of treatment. At Morgan, the warren treated with faeces and one of the warrens treated with urine was recolonised approximately two-three weeks post-collapse. The other warren treated with urine was not recolonised for 12 weeks post-collapse. The control warren was recolonised within 4 weeks. In instances where the area was recolonised, wombats did not dig back into the soft collapsed soil, but rather the surrounding area where the soil had not been disturbed (Figure 5). The model of best fit for the LMM was R1 and included the fixed factor of treatment. Post hoc comparisons revealed no significant difference in the time taken for wombats to recolonise burrows between the control and faeces treatments ($P = 0.839$), and between the control and urine treatments ($P = 0.241$). Examination of the areas surrounding the collapsed warrens found no other new diggings at any of the sites.

Table 2. Comparisons of the LMM used to assess differences in the time taken for wombats to recolonise the collapsed warrens. All models were fitted with the random effect of site. Fixed factors included treatment (Tr), number of wombats (W), complexity of the warren (C), and distance to the nearest warren (D). ΔAIC represents the difference in AIC from the model of best fit, which is highlighted in bold, and wi is the Akaike weight of the model.

Model	Linear form	*df*	Loglik	AIC	ΔAIC	*wi*
R0	1	2	-47.29	98.58	1.6	0.13
R1	**Tr**	**5**	**-43.46**	**96.93**	**0**	**0.29**
R2	Tr + W	6	-42.86	97.73	0.8	0.20
R3	Tr + C	7	-41.83	97.67	0.7	0.20
R4	Tr + D	6	-42.96	97.93	1	0.18

Figure 5. A collapsed warren that had been recolonised. The area circled in yellow shows the location of the original warren.

4.1.3 Visit duration

The top-performing model for the duration of visits to the burrows was D1 (Table 3). It contained the fixed interaction of treatment by trial phase. Post-hoc comparisons revealed no significant difference in the duration of visits to the burrows between trial phases for the faeces or urine treatments (*P* = 0.763, *P* = 0.647, respectively, Figure 6). The duration of visits to the control warrens increased significantly following its collapse (*P* = 0.033, Figure 6).

Table 3. Comparisons of the LMM used to assess differences in the duration of visits to the burrows between trial phases. All models were fitted with the random effects of warren by site, night, and warren by site by night. Fixed factors included trial phase (Tp), treatment (Tr), time (T), minimum overnight temperature (Mt), rainfall (R) and moon phase (Mp). ΔAIC represents the difference in AIC from the model of best fit, which is highlighted in bold, and wi is the Akaike weight of the model.

Model	Linear form	*df*	Loglik	AIC	ΔAIC	*wi*
D0	1	4	-1268.2	2544.3	49.4	41.7
D1	**Tp*Tr**	**10**	**-1237.5**	**2494.9**	**0**	**0**
D2	Tp*Tr/T	15	-1232.1	2496.1	1.2	26.7
D3	Tp*Tr + Mt	11	-1236.7	2496.4	1.5	7.7
D4	Tp*Tr + Mp	14	-1233.6	2495.2	0.3	6.9
D5	Tp*Tr/+ R	11	-1236.7	2495.4	0.5	6.4

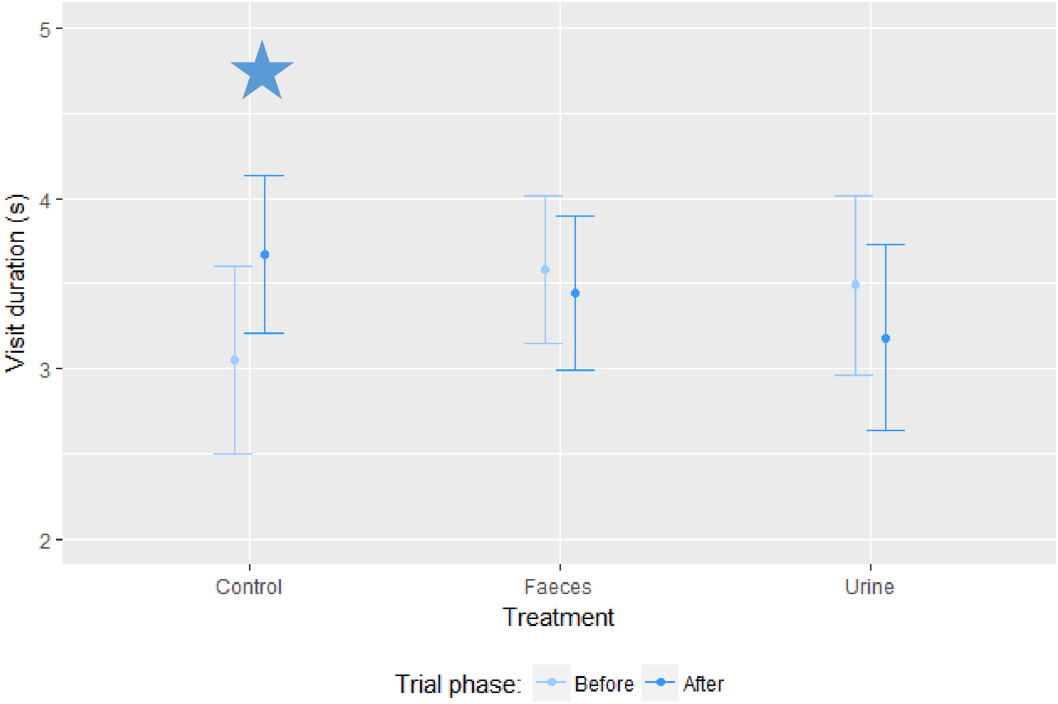

Figure 6. Comparison of the duration of visits (mean and 95% confidence intervals) wombats made to the burrows before and after warren collapse, for the control, faeces, and urine treatments, derived from the model of best fit. The blue star denotes a significant result.

4.1.4 Number of visits

The best performing GLMM for the number of visits to the burrows was V1, which contained the fixed interaction of treatment by trial phase (Table 4). Post-hoc comparisons revealed no significant difference in the number of visits to the burrows, between the trial phases for the urine or faeces treatments (*P* = 0.798, *P* = 0.459, respectively, Figure 7). The number of visits to the warren increased significantly following its collapse for the control treatment (P = 0.001, Figure 7).

Table 4. Comparisons of the GLMM that assessed differences in number of visits *Wombat* made to burrows between trial phases. All models were fit with a negative binomial distribution and the random interaction effect of warren by site. The fixed variables include, trial phase (Tp), treatment (Tr), time (T), minimum overnight temperature (Mt), rainfall (R) and moon phase (Mp). ΔAICc represents the difference in AIC from the model of best fit, highlighted in bold, and *wi* is the Akaike weight of the model.

Model	Linear form	*df*	Loglik	AIC	ΔAIC	*wi*
V0	1	2	-357.93	719.86	27.0	<0.001
V1	**Tp*Tr**	**8**	**-337.98**	**691.97**	**0**	**0.47**
V2	Tp*Tr + Mt	9	-337.96	693.92	2.2	0.15
V3	Tp*Tr + Mp	9	-337.91	693.83	2.1	0.16
V4	Tp*Tr/+ R	9	-337.63	693.27	1.6	0.21

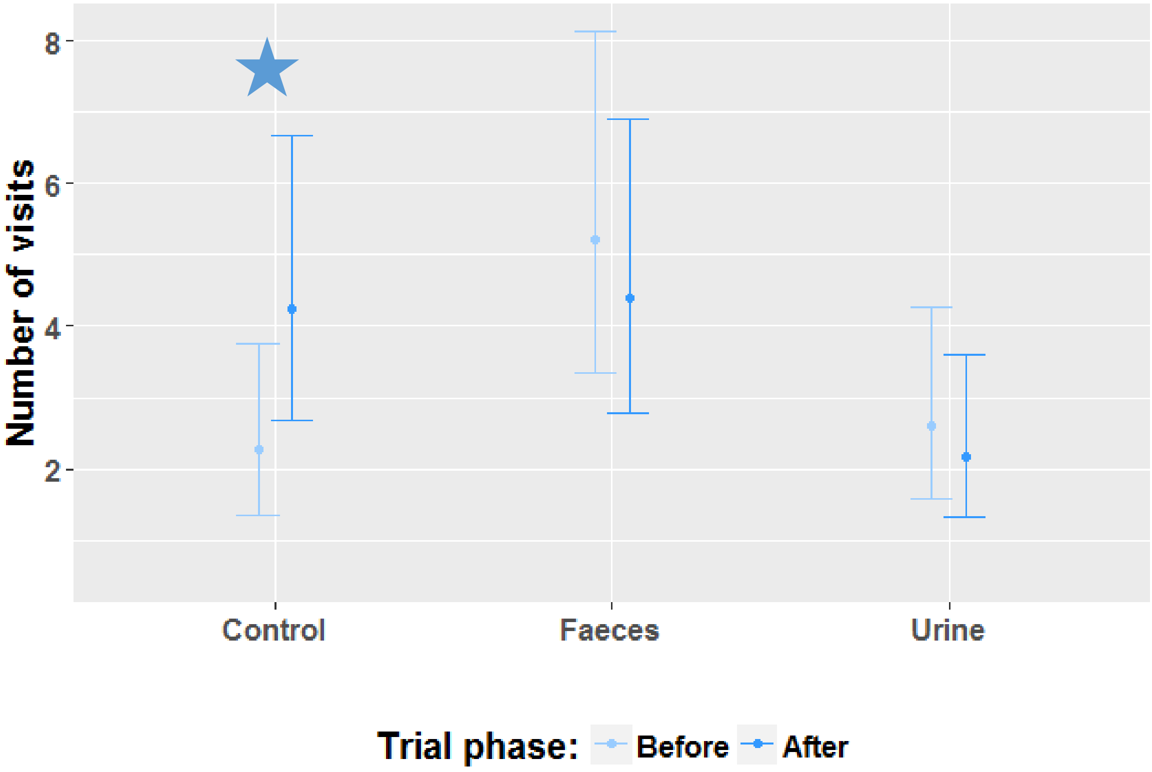

Figure 7. Comparisons of the number of visits (mean and 95% confidence intervals) wombats made to the burrows before and after warren collapse, for the control, faeces, and urine treatments, derived from the model of best fit. The blue star denotes a significant result.

4.1.5 Behavioural analyses

The top-performing model for exploratory behaviour was BE1; it contained the treatment by trial phase interaction (Table 5). Post-hoc comparisons revealed a significant decrease in the proportion of time wombats were observed in exploratory behaviour following the application of urine and faeces (*P* = 0.0006, *P* = 0.00002 respectively, Figure 8). There was no significant difference in the proportion of time wombats spent in exploratory behaviour between trial phases for the control treatment (*P* = 0.382, Figure 8). For resting behaviour, the top performing model was BR1, which contained the treatment by trial phase interaction (Table 5).There was no significant difference in the proportion of time *Wombat* were observed in resting behaviour between trial phases for the faeces and control treatments (*P* = 0.175, *P* = 0.943, respectively,). The proportion of time spent in resting behaviour declined significantly following the application of urine (*P* = 0.005). The model of best fit for vigilant behaviour was BV0 (Table 5). In the next best model, BV1, there was no significant difference in the proportion of time wombats were observed digging between trial phases for the urine or faeces treatments (*P* = 0.930, *P* = 0.973 respectively, Figure 8). The proportion of time wombats spent in vigilant behaviour decreased significantly following burrow collapse at the control treatment (*P* = 0.008, Figure 8).

The top-performing model for travelling behaviour was the intercept-only model, BT0 (Table 5). There was no significant difference in the proportion of time wombats were observed in travelling behaviour between trial phases for the urine, faeces and control treatments (*P* = 0.891, *P* = 0.410, *P* = 0.872 respectively, Figure 8). For unknown behaviour, the best-fit model was BU0 (Table 5). There was no significant difference in the proportion of time wombats were observed in unknown behaviour between trial phases for the urine, faeces, and control treatments (*P* = 0.842, *P* = 0.786, *P* = 0.998 respectively, Figure 8). The best-fit model for digging behaviour was the null model, BD0 (Table 5). There was no significant difference in the proportion of time wombats were observed digging between trial phases for the urine, faeces, or control treatments (*P* = 0.399, *P* = 0.997, *P* = 0.998 respectively, Figure 1Figure 8).

Table 5. Comparisons of the mixed-effects beta regression models used to assess differences in the proportion of time Wombat spent in individual behaviours between trial phases. All models included the random effect of warren by site. The fixed factors included, trial phase (Tp), treatment (Tr), time (T), minimum overnight temperature (Mt), rainfall (R) and moon phase (Mp). ΔAICc represents the difference in AIC from the models of best fit (highlighted in bold), and wi is the Akaike weight of the model.

Model	**Linear form**	***df***	**Loglik**	**AIC**	**ΔAICc**	***wi***
Exploratory						
E0	1	3	2331.32	-4656.64	26.9	<0.001
E1	**Tp*Tr**	**8**	**2349.75**	**-4683.50**	**0**	**0.526**
BE2	Tp*Tr /T	14	2351.73	-4675.46	8.0	0.009
BE3	Tp*Tr + R	9	2349.96	-4681.92	1.6	0.238
BE4	Tp*Tr +Mp	12	2350.10	-4676.20	7.3	0.013
BE5	Tp*Tr + Mt	9	2349.84	-4681.68	1.8	0.211
Resting						
BR0	1	3	2616.34	-5226.68	7.6	0.012
BR1	**Tp*Tr**	**8**	**2625.14**	**-5234.28**	**0**	**0.541**
BR2	Tp*Tr /T	14	2626.66	-5225.32	9.0	0.006
BR3	Tp*Tr + R	9	2625.17	-5232.34	1.9	0.205
BR4	Tp*Tr + Mp	12	2625.88	-5227.76	6.5	0.021
BR5	Tp*Tr + Mt	9	2625.21	-5232.42	1.9	0.213
Travelling						
BT0	**1**	**3**	**2475.33**	**-4944.66**	**0**	**0.949**
BT1	Tp*Tr	8	2476.90	-4937.80	7	0.028
BT2	Tp*Tr /T	14	2478.31	-4928.62	16.6	<0.001
BT3	Tp*Tr + R	9	2476.91	-4935.82	9.1	0.010
BT4	Tp*Tr + Mp	12	2477.49	-4930.98	14.1	<0.001
BT5	Tp*Tr + Mt	9	2477.04	-4936.08	8.8	0.012
Vigilant						
BV0	**1**	**3**	**2582.43**	**-5158.86**	**0**	**0.405**
BV1	Tp*Tr	8	2587.02	-5158.04	0.8	0.269
BV2	Tp*Tr /T	14	2588.37	-5148.74	10.1	0.002
BV3	Tp*Tr + R	9	2587.16	-5156.32	2.5	0.114
BV4	Tp*Tr +Mp	12	2587.36	-5150.72	8.1	0.006
BV5	Tp*Tr + Mt	9	2587.73	-5157.46	1.4	0.201
Digging						
BD0	**1**	**3**		**5967.44**	**0**	**0.889**
BD1	Tp*Tr	8		5961.70	5.7	0.050
BD2	Tp*Tr /T	14		5950.92	16.5	<0.001
BD3	Tp*Tr + R	9		5959.76	7.7	0.019
BD4	Tp*Tr +Mp	12		5954.34	13.1	0.001
BD5	Tp*Tr + Mt	9		5961.22	6.2	0.039
Unknown						
BU0	**1**	**3**	**2732.39**	**-5458.78**	**0**	**0.97**
BU1	Tp*Tr	8	2733.05	-5450.10	8.7	0.012
BU2	Tp*Tr /T	14	2733.54	-5439.08	19.7	<0.001
BU3	Tp*Tr + R	9	2733.07	-5448.14	10.6	0.004
BU4	Tp*Tr + Mp	12	2733.70	-5443.40	15.4	<0.001
BU5	Tp*Tr + Mt	9	2733.06	-5448.12	10.7	0.004

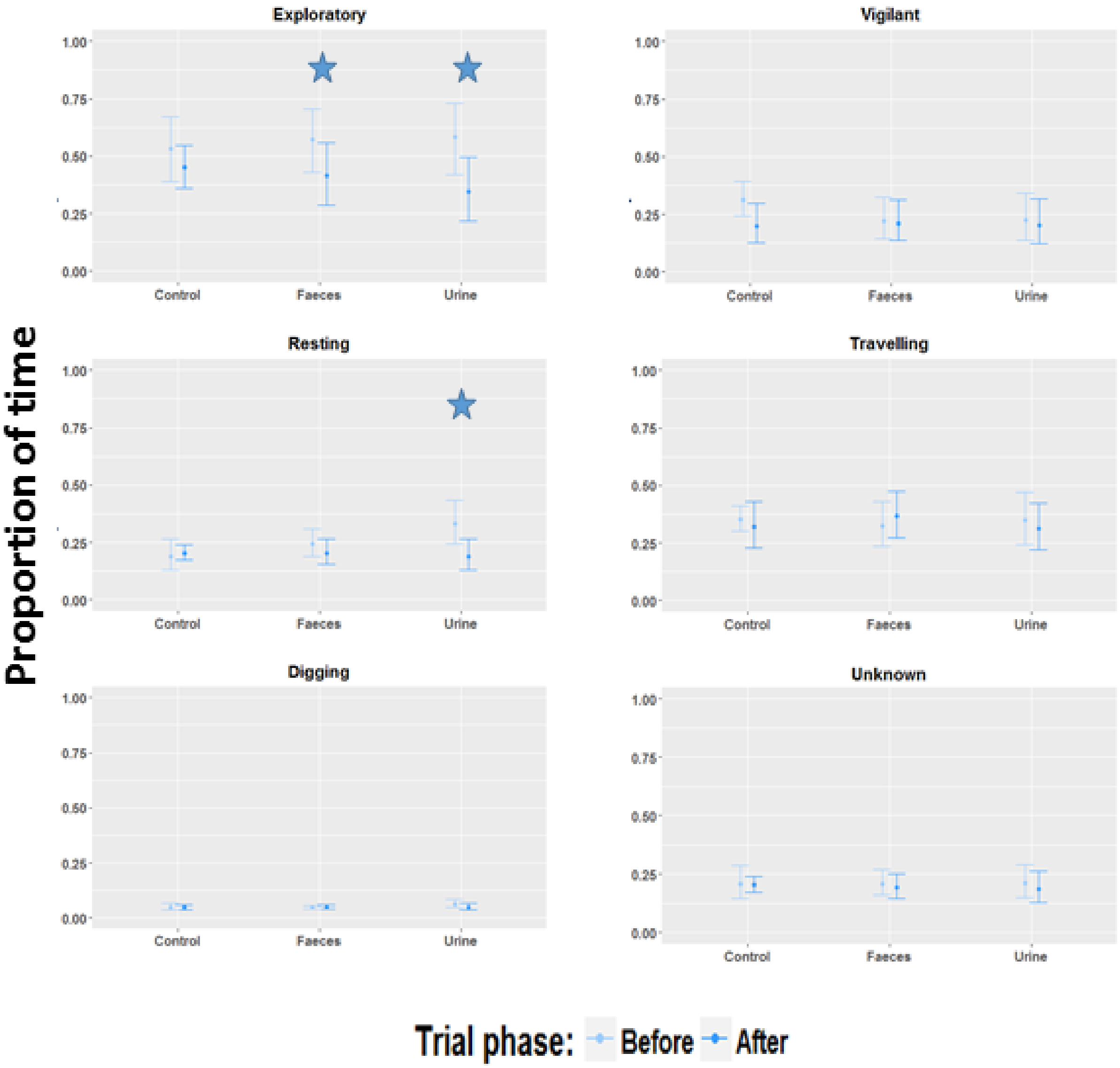

Figure 8. Comparisons of the proportion of time (mean and 95% confidence intervals) wombats spent in the six behaviours observed, before and after warren collapse, for the control, faeces, and urine treatments, derived from the model of best fit. The blue stars denote significant results.

5. Discussion

This study examined the effectiveness of burrow collapsing and predator odour deterrents in reducing the damage wombat warrens cause to agricultural properties. Trials were conducted across three private properties, on each of which four small warrens were selected for the trials. Following a two week control period where warrens were monitored with motion sensor cameras, warrens were gradually collapsed over three days. The process of gradually collapsing warrens was successful in encouraging wombats to leave their burrows by the third day 93% of the time. Once collapsed the warrens were treated with either 200ml of dog urine, 200g of dingo faeces or left as a control. Fifty-eight percent of the warrens were recolonised within a month of being collapsed. The treatments had no significant effect on the time taken for wombats to recolonise warrens. There was wide variation in results between the properties, suggesting there may be other environmental factors influencing the time taken for wombats to recolonise warrens. Further research is recommended to increase the sample size and provide greater clarity on the importance of habitat, soil type, warren availability, and warren size/depth for the successful exclusion of wombats from warrens.

5.1.1 Burrow collapsing

The time taken to collapse small wombat warrens containing 1-5 burrows ranged from 1½ – 10 hours, and cost between $600-1,500. The costs of collapsing warrens were reduced in our study, by collapsing warrens using crowbars and shovels over the first two days. This may not be possible in all circumstances, due to differing soil types and burrow depths, further increasing the costs of collapsing warrens. The time and costs associated with ripping wombat warrens may be prohibitive on a small landholder scale. Excluding wombats from their warrens using one-way gates and partially collapsing burrow entrances using a grader (a piece of machinery most farmers own) may be more economically viable for many landholders; however, the effectiveness of these measures is unknown.

The gradual collapsing of wombat warrens over a three day period, resulted in the successful evacuation of wombats from 93% of burrows. In the two instances wombats failed to leave warrens, they were left open for a fourth night. One wombat remained in its burrow and further excavated it. The failure of wombats to leave disturbed warrens may reflect the importance of the warren, with animals being more difficult to deter from limited resources or areas where they are already established (Koehler *et al.* 1990; Gilsdorf *et al.* 2002). Burrows are critical to the survival of wombats, they are territorial and display strong fealty towards them. Although wombats may use up to 10 different warrens within their home range they usually use 1-2 warrens on the majority of occasions (Shimmin *et al.* 2002; Finlayson *et al.* 2005). Despite there being alternative warrens in the near vicinity (≤ 50m away) with inactive burrows, they could have been excluded from accessing them by neighbouring wombats, or perhaps they were unsuitable for other reasons.

5.1.2 Recolonisation

Collapsed wombat warrens were recolonised within a month in 58.3% of cases, while the remaining warrens were not recolonised for ≥ six months post collapse. The collapsing of warrens did not appear to shift the problem elsewhere, with no new excavations observed within a 200m radius of the collapsed warren. In contrast to this study, the exclusion of badgers from setts using one-way gates was successful in 62% of cases, however, this was based on the absence of badger activity for a 21 day period (Ward 2007). In comparison to the time spent monitoring badger setts, this study produced a similar 58% success rate over a 21 day period. The factors influencing the success of wombat exclusions are unknown. Exclusions of badgers from main setts, in which they spend most of their time were more likely to fail than exclusions from outlier setts (Ward *et al.* 2016). Similarly, wombats spend the majority of their time in 1-2 main warrens (Finlayson *et al.* 2005), and excluding them from main warrens may prove less successful; however, identifying main and outlier warrens was beyond the scope of this study. Further research is needed to examine wombat ranging behaviour before and after warren collapse. This information may provide greater clarity on the importance of habitat, soil type, availability of alternative warrens, and warren characteristics, for the successful exclusion of wombats from warrens. The repeated disturbance of the problem warrens following recolonisation may prove effective in preventing ongoing conflicts. The ripping of rabbit warrens every 12 months has been found to significantly reduce their presence (McPhee and Butler 2010). Wombat warrens are often significantly larger and deeper than rabbit warrens, and would likely require a much larger investment of time and money and thus may prove too costly.

The application of dog urine and dingo faeces had no significant impact on the time taken for wombats to recolonise collapsed warrens. There was wide variation in recolonisation rates within and between sites regardless of treatment, suggesting recolonisation may be influenced by other environmental factors, but they were unable to be identified due to the small sample size. Though no difference in recolonisation rates was observed between odour treated warrens, there was a significant increase in the number and duration of visits to the control warrens following collapse. Given the warrens were 200m apart the increase in visitation rates is unlikely to be a residual effect of the odour treatments. Thus, although a significant difference in visitation rates was not found following warren collapse, the dingo urine and faeces may have prevented an increase in visitation, as observed for the controls. This is supported by a significant decrease in exploratory and resting behaviour at the odour treated warrens following burrow collapse.

In contrast to these results, Sparrow *et al.* (2016) found wombats on the Nullarbor took longer to recolonise collapsed burrows treated with dingo urine and faeces. The differences in results could be due to context dependent differences between the studies, or differences in the methods used to analyse data. Variation in predator numbers can function as a level of risk, with predators that are encountered more frequently posing a greater threat than those in lower densities. This has been observed in gerbils (*Gerbillus andersoni allenbyi*), whose anti-predator responses intensified with increasing numbers of barn owls (*Tyto alba*) (St Juliana *et al.* 2011). Wombats on the Nullarbor may encounter dingos or wild dogs more regularly than those in the Murraylands, due to their proximity to the dog proof fence (South Australian Wild Dog Advisory Group 2016). The physical absence of predators from the study sites may therefore limit the effectiveness of their odour cues. An initial physical encounter or repeated exposure to dingos/wild dogs may be required to elicit an avoidance response. The samples used in this study were frozen due to the difficulty in maintaining a large volume of fresh supplies, whereas Sparrow *et al.* (2016) used fresh samples. Freezing the samples could have resulted in reduced repellency, as the chemical composition of voids may break down following freezing, altering the stability of the messages contained within them (Schultz *et al.* 2000). However, frozen voids have produced avoidance responses in captive *wombats* (Descovich *et al.* 2012), and rodents (Hayes *et al.* 2006; Russell and Banks 2007). There may have also been a range of differences in the habitat and environmental variables that affected the results.

5.2 Recommendations

Trials on non-lethal wombat management techniques were conducted across three properties within the rangelands. On each property, four small warrens (1-5 burrows) were gradually collapsed across three days. The gradual collapsing of warrens was 93% successful in encouraging wombats to leave their warrens by the third day on which they were completely ripped. Warrens were then treated with either 200ml of dog urine, 200g of dingo faeces, or left as an untreated control. Within one month post collapse 58% of the collapsed warrens were recolonised. The remaining 42% of warrens were not recolonised for ≥ 6 months post collapse. The treatments of dog urine and dingo faeces had no significant effect on the time taken for wombats to recolonise warrens. There was wide variation in the results between the three properties, suggesting there may have been other environmental factors influencing the results.

Based on the findings from these trials, wombat warren ripping does not appear to be a sustainable long-term solution to resolving human-wombat conflict. Though the exclusion of wombats from warrens using the gradual collapse method was successful in 93% of cases, the ripping of warrens only reduced damages for ≥ six months in 41.7% of cases and proved to be time consuming and costly. The application of dog urine and dingo faeces did not significantly reduce the time taken for wombats to recolonise collapsed warrens; however, there was wide variation in results within and between sites. This suggests there may be other environmental factors affecting the success of warren collapsing, but due to the small sample size, this was unable to be determined. A larger study, assessing the ranging behaviour of wombats before and after burrow collapse may provide greater clarity on the importance of habitat, and warren availability and type for the successful exclusion of wombats from their warrens, and assist wildlife managers in determining if burrow collapsing is the most appropriate course of action. Although burrow collapsing is considered non-lethal, its impact on wombats is poorly understood, assessing wombat spatial behaviour before and after warren collapse will also provide vital information on the impact of warren collapsing on wombat welfare. Assessing the effectiveness of one-way gates in excluding wombats from their warrens and partially collapsing burrow entrances using a grader, are recommended for future research due to their potential cost effectiveness. Further testing of other potential deterrents and/or physical barriers, including predator sound recordings; chain-link or mesh netting to reduce wombat recolonization rates post warren collapse are also recommended.

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