Title: Fear on the Landscape: How human activity shapes wildlife habitat use in protected areas in Tasmania

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Author contributions

Laura M. Cardona, Jessie C. Buettel and Barry W. Brook conceived the ideas and designed the methodology. Jessie C. Buettel and Barry W. Brook contributed to data analysis and to drafts of the paper. Laura M. Cardona analysed data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Abstract

The growing enthusiasm for outdoor recreation has prompted questions about the effects of different forms of human activity on the habitat use of both predators and prey. Here, we used time-to-event camera trap data from a large-scale survey in Tasmanian protected areas to investigate the influence of motorised (vehicles) and non-motorised (hikers, joggers, and cyclists) recreation on wildlife return times - the time between consecutive detections of the same species – during the warm and cold season. Specifically, we focused on the Tasmanian devil (*Sarcophilus harrisii*), the apex predator in this system, and four common herbivore species: brushtail possums (*Trichosurus vulpecula*), Tasmanian pademelons (*Thylogale billardierii*), Bennett's wallabies (*Notamacropus rufogriseus*), and bare-nosed wombats (*Vombatus ursinus tasmaniensis*). We found that more motorised and non-motorised events delayed Tasmanian devil return times in both seasons. For herbivores, all species showed longer return times under motorised activity irrespective of season, whereas non-motorised activity had no significant effect on wallabies during the cold season. These results indicate that predator and prey perceive both forms of human activity as a source of risk. This study demonstrates the utility of time-to-event data from camera traps for testing the influences of different disturbance sources on wildlife. These insights are vital for managers striving to balance public access with conservation goals in protected areas.

Introduction

Protected areas (PAs) are an important governance mechanism for wildlife conservation (Leader-Williams *et al.,* 1990; Lockwood *et al.,* 2006; Dudley *et al.,* 2010). They aim to act as refuges for species and maintain ecological processes such as predator-prey systems (Arcese *et al.,* 1997). In Tasmania, Australia, the PA network is critically important for biodiversity conservation, covering nearly half of the island's total land area, which is designated as reserves or national parks (Mendel *et al.,* 2002;

Davidson *et al.,* 2021). This extensive network has provided refuge for iconic species that are extinct on the mainland, including the world's largest extant marsupial carnivore, the Tasmanian devil (*Sarcophilus harrisii*) (Hollings *et al.,* 2014). Many of these PAs also accommodate public access for recreation through designated road networks (Tasmania Parks and Wildlife Service 2025) and, as such, have historically operated under a dual mandate: to provide opportunities for human activity while ensuring wildlife conservation.

In recent years, tourism to the island and the popularity of outdoor recreation has increased, and so too have visitation and length of stay to PAs (Balmford *et al.,* 2009; Hardy *et al.,* 2020; Beery *et al.,* 2021; Tasmania Parks and Wildlife Service 2024). Increased recreation has been shown to affect the behaviour and spatiotemporal distribution of wildlife species (Larson *et al.,* 2016). In some systems, species have shifted to more nocturnal activity (Lewis *et al.,* 2021b; Salvatori *et al.,* 2023), delayed their return to trails and roads (Naidoo *et al.,* 2020a; Visscher *et al.,* 2023), and reduced their use of these features with increased human presence (Gump *et al.,* 2023). Other species have been found to use increase their occupancy and habitat use of recreational trails (Lewis *et al.,* 2021b; Gump *et al.,* 2023), or to shift their activity patterns to better align with periods of high human activity (Sytsma *et al.,* 2022).

Understanding how human activity affects wildlife behaviour and distribution in PAs is important for evaluating their effectiveness in maintaining ecosystem functioning (Reed *et al.,* 2008; Sytsma *et al.,* 2022) and devising effective management strategies (Monz *et al.,* 2013). Nevertheless, such assessments are challenging, because wildlife responses to recreation are shaped by multiple factors (Marion *et al.,* 2020). These responses depend not only on the intensity of human activity but also on its type, the spatial and temporal context (e.g. season), and species-specific ecological and life history traits (Tablado *et al.,* 2017). For instance, some mammal species have been shown to be deterred by non-motorised activities (e.g. hikers and bicycles) but attracted to motorised activities (e.g. vehicles) (George *et al.,* 2006b; Procko *et al.,* 2022; Gump *et al.,* 2023). Predator and prey responses to human activity have been found to vary across systems, ranging from mutual avoidance to mutual attraction (Van Scoyoc *et al.,* 2023), and cases where prey are attracted to humans for resources or safety while predators avoid them (Berger 2007; Rogala *et al.,* 2011b).

To address this challenge, ground-deployed autonomous technology, such as camera traps (CTs), offers a promising approach. CTs are well-established tools that allow researchers to survey multiple mammal species continuously across various landscapes and over extended periods (Swann *et al.,* 2011; Steenweg *et al.,* 2017; Kays *et al.,* 2020). Recent advances in machine learning approaches and artificial intelligence to automate image identification and anonymise human records, have revolutionised the type of information that can be extracted and analysed from such data (Miller *et al.,* 2017; Tabak *et al.,* 2019; Fennell *et al.,* 2023; Vélez *et al.,* 2023). Simultaneously, the proliferation of statistical and computational models for camera data has enabled robust approaches to assess species behaviour, habitat use and interactions while controlling for confounding factors (Sollmann 2018). As a result, CTs applications have expanded to include quantification of human presence and activities facilitating better understanding of human-wildlife interactions (Miller *et al.,* 2017; Cardona *et al.,* 2024).

To-date however, there has been relatively limited application of CTs to monitor wildlife responses to different types of human activity (Cardona *et al.,* 2024). Furthermore, studies have often pooled wildlife data by seasons, weeks or days and additional research on finer-scale changes (e.g. hourly) is needed (Naidoo *et al.,* 2020a; Blount *et al.,* 2021; Gump *et al.,* 2023; Marion *et al.,* 2024). Time-to-event data obtained from CTs, provides a powerful approach to detecting short term shifts in wildlife temporal and spatial use of habitats that otherwise would not be detected when pooling data into days or weeks. By calculating the time elapsed between a specific event (e.g. species A) and its subsequent detection (A to A) (Niedballa *et al.,* 2019), changes in the time it takes for an animal to reuse an area can be identified and the impact of other wildlife and/or human activity (e.g. species B between A to A) can be explored (Paull *et al.,* 2012; Visscher *et al.,* 2023; Ferry *et al.,* 2024).

In this study, we used camera-trap time-to-event data to assess short-term changes in wildlife spatiotemporal habitat use in response to different types of human activity in Tasmanian PAs. Specifically, we examined the effects of motorised and non-motorised activities on the time it took the apex predator, the Tasmanian devil, and four herbivore species to return to a previously visited CT site (return time). These herbivores included medium-to-large marsupials species that are also prey of the Tasmanian devil (Pemberton *et al.,* 2008; Andersen *et al.,* 2017): brushtail possum (*Trichosurus vulpecula*, hereafter 'possum'), Bennett's wallaby (*Notamacropus rufogriseus*, hereafter 'wallaby'), red-bellied or Tasmanian pademelon (*Thylogale billardierii*, hereafter 'pademelon'), and bare-nosed or 'common' wombat (*Vombatus ursinus tasmaniensis*, hereafter 'wombat'). Despite the common status and wide distribution of these species in Tasmania, information on their responses to recreational activity is relatively limited. Given evidence that wildlife exhibit spatiotemporal avoidance of increased vehicle and pedestrian presence (Frid *et al.,* 2002; Gaynor *et al.,* 2018), we predicted that both motorised and non-motorised human activities would prolong the return times of the studied species.

Methods.

Existing field sites and camera deployment

We used time-to-event data derived from a pre-existing camera trap (CT) network established in 2018 for the purpose of wildlife monitoring project across Tasmania, Australia. The study involved 119 camera sites (model: Cuddeback Xchange 1279) located in protected areas (PAs) across the southeastern, central highlands, northwestern and western regions (Figure 1). These PAs comprised National Parks, Conservation areas, and other reserves (see Table S1 for the list of protected areas), and covered a variety of habitat types, from temperate forests such as Eucalypt woodlands and tall open forests, to grasslands, herb lands, sedgelands, bushlands, rainforests, vine thickets, low closed forests, and tall closed shrublands. A wide range of non-consumptive human activities take place within these areas during both day and night, such as camping, hiking, vehicle driving, dog walking, fishing, mountain biking, four-wheel driving, all-terrain vehicle (ATV) driving and boating. These activities are regulated through existing management policies and educational programs (Tasmanian government 2021). Native forest extraction and wildlife hunting is prohibited, and activities such as four-wheel-driving, walking dogs and hiking are restricted to designated areas and roads. Over the past decade, public interest in outdoor recreation and nature-based activities in Australia has increased (Hardy *et al.,* 2020; Ecotourism Australia 2023), resulting in higher visitation to many of these PAs (Tasmania Parks and Wildlife Service 2024).

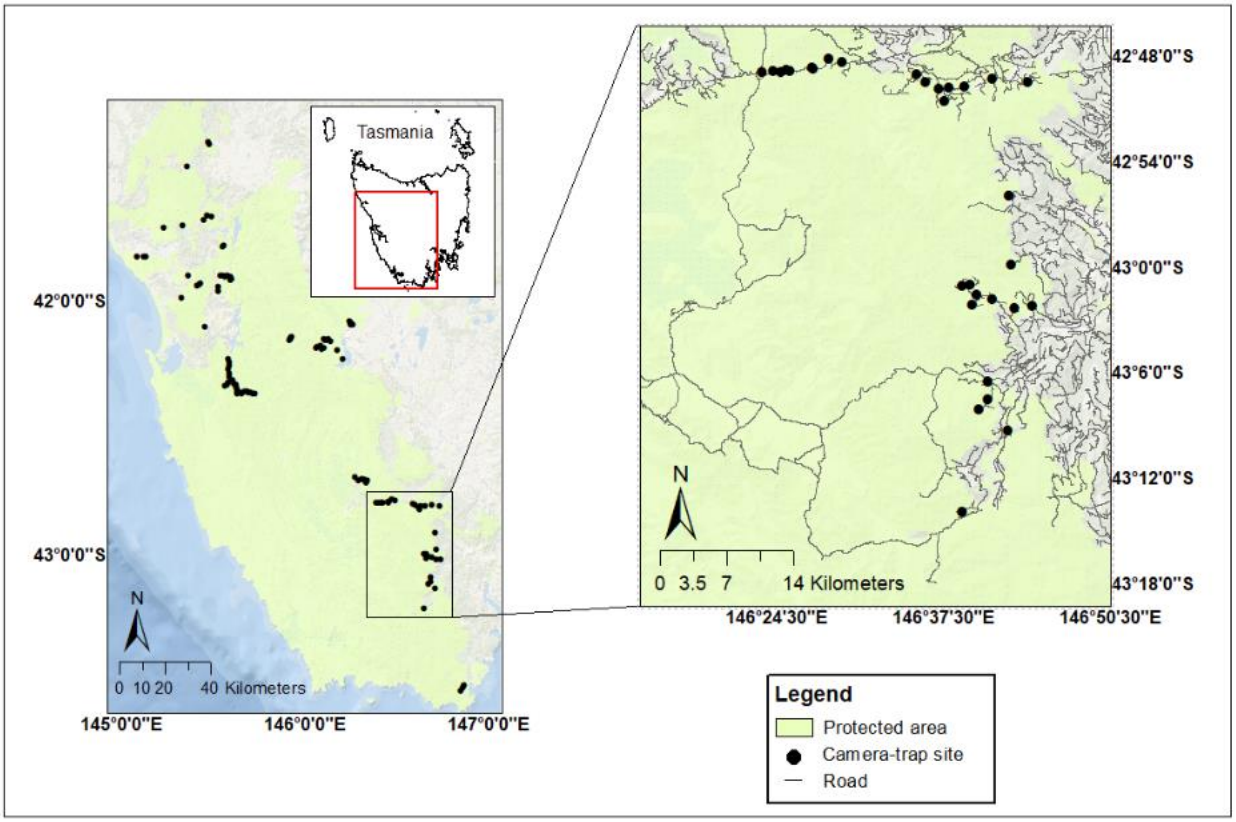

Figure 1. Map of Tasmania showing the camera trap sites located along unsealed roads used in this study (black points). The green shaded area indicates the boundary of the protected areas (obtained from the Tasmanian Reserve Estate spatial layer). The map on the right shows an example of the camera deployments at a finer spatial scale.

Cameras were placed along unsealed roads (gravel or dirt roads). We acknowledge that road- based designs limit results to the habitat use of wildlife and humans to roads rather than the whole study area. Nevertheless, restricting cameras to roads eliminated confounding effects associated with edge-effects, such as shifts in community composition and variation in detection probabilities, that arise when sampling designs include both on- and off-road locations (Fuentes-Montemayor *et al.,* 2009; Bötsch *et* *al.,* 2018b; Greco *et al.,* 2025). Study designs that exploit roads are also more cost effective (Geyle *et al.,* 2020), efficient for detecting large mammals and carnivores (Mann *et al.,* 2015; Tanwar *et al.,* 2021), and allow researchers to directly and simultaneously monitor human activity and wildlife (Wolf *et al.,* 2012; Miller *et al.,* 2017; Oberosler *et al.,* 2017; Salvatori *et al.,* 2023; Procko *et al.,* 2024). Accordingly, this approach was functional to our research aims.

Cameras were at least 100 m apart (typically 250 m to 5 km), not baited and fixed to stakes or trees at an average height of 30 cm off the ground, adjusted to target medium to large mammal species. They were equipped with a passive motion sensor and either an infra-red or white flash, depending on the perceived risk of theft in the area. Infra-red cameras were programmed with 30-second delay for both day and night, while white flash units operated with 30-second delay during the day and one minute at night. Cameras were re-visited and serviced every 4-6 months to retrieve the images, replace batteries, remove vegetation obstructing the lens, and check for any theft occurrences. Camera-trap imagery for this study was collected over a four-year period, from July 2018 to June 2022. A total of 92 cameras were deployed in 2018 (and remained in place throughout the study), with an additional 23 cameras added in 2019, followed by one in 2020, and three in 2021. Before the end of the four-year period a total of 18 CTs were stolen. In total, the 119 camera traps operated for 93,622 days (average of 787 days, or 2.16 years, of cumulative operation per camera site).

Data analysis

Determining independent events of wildlife and humans

To address temporal autocorrelation, we first identified independent events (hereafter 'events') in the camera-trap imagery of humans and wildlife. Independent events for wildlife species – possums, wallabies, pademelons, wombats and Tasmanian devils – were defined as detections of the same species occurring at least 30 minutes apart at each camera-trap site. This threshold, based on prior studies in similar mammal communities (Cunningham *et al.,* 2019), minimises the likelihood of repeat detections of the same individual or group. Applying this criterion resulted in 10,257 events for pademelons, 8,034 for possums, 8,943 for wombats, 3,126 for wallabies, and 9,230 for Tasmanian devils.

Camera trap imagery was processed using the open-source object detection software MegaDetector v5 (Beery *et al.,* 2019a), using a confidence threshold of 50% (Brook *et al.,* 2025). This automated approach identifies vehicles and people from remote camera data (Fennell *et al.,* 2022), and enables classification without viewing images, thereby preserving individual privacy. We categorised vehicles as 'motorised' forms of activity (vehicles other than bicycles), and people as 'non-motorised' forms of activity (people on foot and on bicycles) (Reilly *et al.,* 2017; Procko *et al.,* 2022; Gump *et al.,* 2023). To define independent events we applied a one minute threshold, as longer intervals risked conflating distinct events given the rapid passage of vehicles and pedestrians (Procko *et al.,* 2022). This resulted in 21,972 events of motorised activity, and 2,875 of non-motorised activity.

Model design

All analyses were undertaken in Program R v4.3 (R Development Core Team 2010).

We used a statistical time-to-event analysis based on a mixed-effects Cox proportional hazards model (Cox 1972) from the R package 'coxme' (Therneau 2015). This model was used to examine 'return times' of possums, pademelons, wallabies, wombats and Tasmanian devils, defined as the time difference (in hours) between the end of one event of a species and the beginning of the next consecutive event of the same species (Figure 2a) (Visscher *et al.,* 2023). Return times were calculated for each camera operational period (hereafter 'period'), which was defined as the duration during which a camera remained continuously active. A period ended when a camera either malfunctioned (e.g., stopped operating due to battery depletion), was stolen, or reached the end of the field season. Because cameras could malfunction between servicing visits, some camera sites had multiple periods. Unlike return times of marked individuals commonly measured using GPS telemetry (Anderson *et al.,* 2008; English *et al.,* 2014; Martin *et al.,* 2015), our approach focused on revisit times of an animal to fixed camera-trap sites, thus capturing data at the population level.

To meet the proportional hazards assumption of the Cox model, and focus on an ecologically relevant timeframe, return times were left- and right-censored (Rulli *et al.,* 2018; Visscher *et al.,* 2023). We left-censored return times at five hours, as shorter intervals likely reflect immediate local foraging rather than meaningful habitat revisits from a risk-avoidance perspective (See Figure S1 for the distribution of return times for all four species). Right-censoring was set at 24 hours to restrict analyses to single diel cycles, as longer thresholds risk introducing non-proportional effects due to repeated daily patterns in disturbance sources (e.g. human and predator activity patterns) and animal behaviour that could confound covariate estimates (Fisher *et al.,* 1999). To account for variation across sites such as potential differences in animal densities, and to address the non-independence of observations within camera-trap locations, site was included as a random intercept.

Model covariates

We modelled wildlife return times using two continuous predictor variables: the number of motorised and the number of non-motorised events recorded during each return interval (Figure 2b). Representing these predictors as continuous counts, rather than binary presence-absence indicators, allowed us to quantify how each additional event – regardless of whether it occurred during the day or night – influenced wildlife return times. All three predictors were included in the modelling as they all had a Pearson's correlation coefficient r < 0.7. We did not undertake model selection as we were interested in effect size rather than predictive modelling (as per the recommendation of Yates *et al.,* 2023).

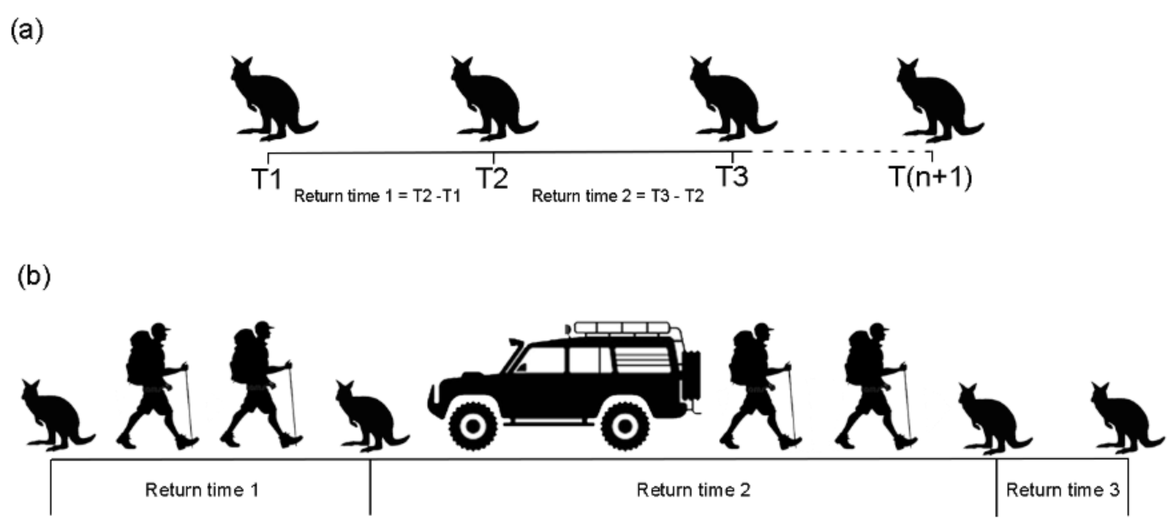

Figure 2. A timeline illustration of (a) the procedure to calculate return times (RTs) using time-to-event-data from a single camera trap**.** T1 is the time (in hours) elapsed from the moment the camera started operating to the moment it captured the first event of a mammal species. T2, T3 and next

T_i values are the times for subsequent independent events (using a threshold of 30 minutes) of that same species. T_{n+1} is the time of the last independent event of the species before the camera trap stopped operating due to either battery depletion, theft, removal due to high risk of theft, or the end of the study period. RTs are calculated as $RT_i = T_{(i+1)} - T_i$, for i = 1, 2, …, n. (b) scenarios where zero, one, or more than one independent event involving motorised or non-motorised human activity (using a threshold of one minute) occurred during the return time interval of a mammal species.

Hazard modelling framework

Cox proportional hazard models were examined for each wildlife species during two distinct periods of the year, referred to as 'season'. This approach allowed us to minimise the influence of seasonal changes in wildlife and human activity patterns. The 'warm' season encompassed summer and parts of late spring and early autumn, defined as November to March (Southern Hemisphere). This period is characterised by higher average maximum temperatures and greater visitor numbers to Tasmania (Cook *et al.,* 2000; Hardy *et al.,* 2020). In contrast, the 'cold' season spanned April to October and was associated with lower average maximum temperatures. Return times were grouped according to these two seasonal divisions.

For each model, we estimated hazard ratios (HRs) and 95% confidence intervals (CIs) for all predictor variables. The HR represents the multiplicative effect of a predictor on the hazard of a species return time. A HR less than one suggests that the predictor variable reduces the hazard, leading to longer return times. Predictor variables with 95% CI that did not overlap with one were considered to have evidence of an effect on wildlife return times.

Results

Warm season

A total of 4,707 return times were recorded for pademelons, 4,253 for wombats, 3,310 for possums, 1,733 for wallabies, and 3,471 for Tasmanian devils. During the warm season roads averaged approximately 1.83 motorised events per day (range = 1.00–5.59) and 1.49 non-motorised events per day (range = 1.11 – 2.40).

We found that both the number of motorised and non-motorised events had a negative effect on return times for wildlife (see Figure 3 and Table S2 for model outputs). For Tasmanian devils (predator) each additional motorised event delayed return times by approximately 35% (hazard ratio, hereafter HR: 0.65; 95% confidence interval, hereafter CI: 0.59-0.72), while each additional non-motorised event delayed return times by approximately 72% (HR: 0.28; 95% CI: 0.14-0.54). Among herbivores (prey), the longest delay associated with motorised events was for wombats (HR = 0.54; 95% CI:0.48-0.62), and with non-motorised events for possums (HR:0.42, 95% CI:0.28-0.62).

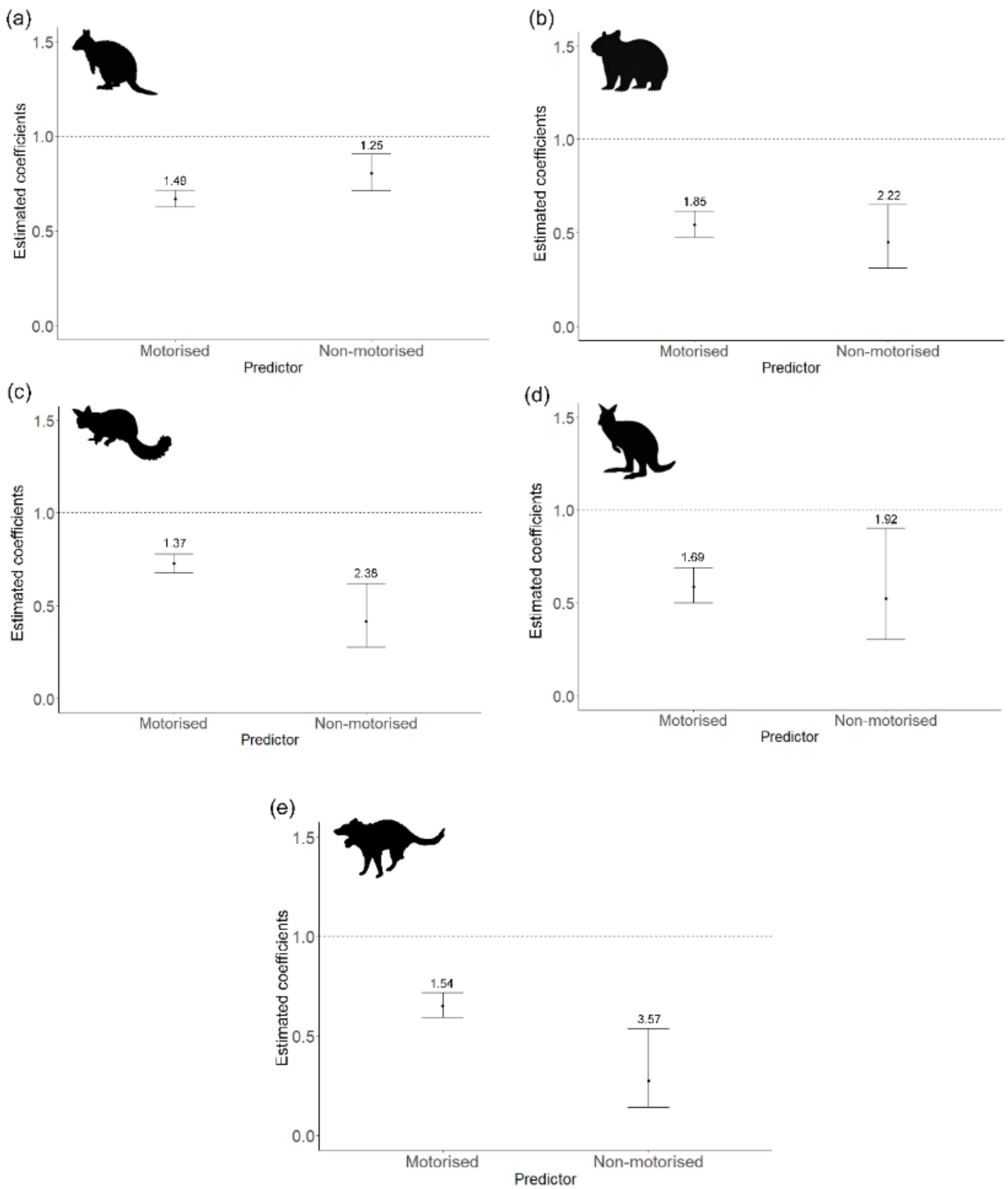

Figure 3. Warm season hazard ratio (HR) estimates and 95% confidence intervals (CIs; vertical lines) of for predictors included in the Cox model for (a) Tasmanian pademelon, (b) Bare-nosed wombat, (c) Brushtail possum (d) Bennett's wallaby, and (e) Tasmanian devil. Predictors with HR was less than one and 95% CI not overlapping with one were interpreted as having a significant negative effect in the hazard, and thus, delaying return times for that species. A HR equal to one indicates no effect. The

numbers above each point on the plot represent the return time multipliers calculated as 1/HR. Predictors include: Motorised = motorised forms of activities (e.g. vehicles and ATVs), and non-motorised = non-motorised forms of activity (e.g. walkers and bicycles).

Cold season

A total of 3,582 return times were recorded for pademelons, 3,198 for wombats, 2,745 for possums, 834 for wallabies, and 4,132 for Tasmanian devils. During the cold season roads averaged approximately 1.54 motorised events per day (range = 1.00 –4.28), and 1.47 non-motorised events per day (range = 1.07 – 2.44).

During the cold season, we found that an increase in motorised events had a negative effect on return times for all wildlife species (see Figure 4 and Table S2 for model outputs). For instance, an additional motorised event delayed return times for Tasmanian devils by approximately 47% and for wallabies by approximately 60% (Figure 4c and e). However, during this season, an increase in non-motorised events significantly delayed return times only for Tasmanian devils (HR: 0.46; 95% CI: 0.30-0.70) and three herbivore species: pademelons (HR: 0.73; 95% CI: 0.58-0.91) wombats (HR: 0.44; 95% CI: 0.34-0.80), and possums (HR: 0.60; 95% CI: 0.44-0.63). This suggests species-specific responses to non-motorised recreation that vary by season, likely driven by lower human visitation levels in Tasmanian protected areas (PAs) during the cold season and behavioural traits associated with individual species.

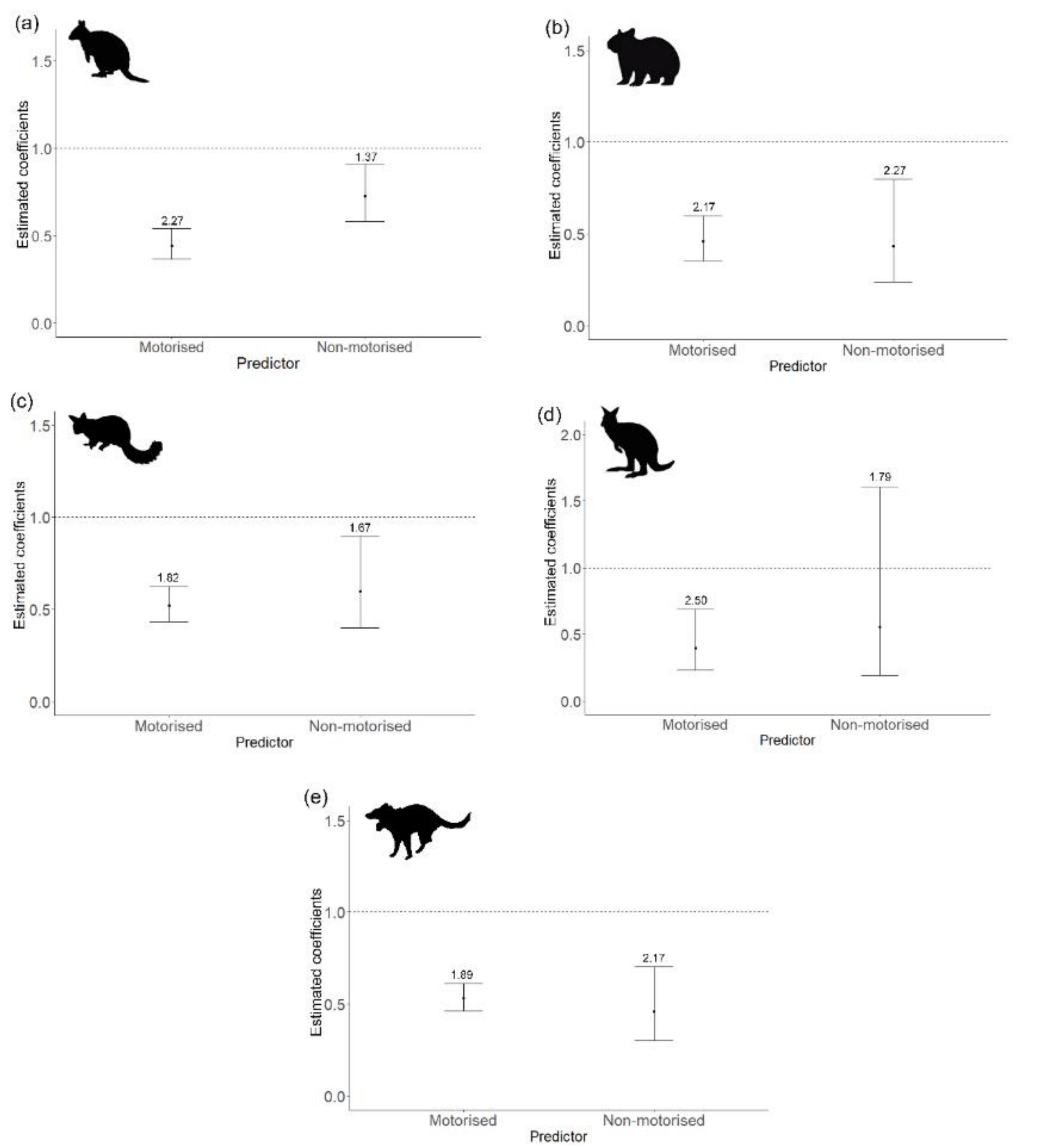

Figure 4. Cold season hazard ratio (HR) estimates and 95% confidence intervals (CIs; vertical lines) of for predictors included in the Cox model for (a) Tasmanian pademelon, (b) Bare-nosed wombat, (c) Brushtail possum (d) Bennett's wallaby, and (e) Tasmanian devil. Predictors with HR was less than one and 95% CI not overlapping with one were interpreted as having a significant negative effect in the hazard, and thus, delaying return times for that species. A HR equal to one indicates no effect. The numbers above each point on the plot represent the return time multipliers calculated as 1/HR. Predictors include: Motorised

= motorised forms of activities (e.g. vehicles and ATVs), and non-motorised = non-motorised forms of activity (e.g. walkers and bicycles).

Discussion

In this study, we used a time-to-event analysis to assess how an increase in the number of events involving motorised and non-motorised recreation influence return times of Tasmanian devils and four prey species, in protected areas (PAs) of Tasmania. The results showed that predator and prey delayed their return times following more motorised and non-motorised events, indicating that they generally avoided human presence along roads.

In line with our predictions, we found that both predator and prey species avoided motorised and non-motorised activities along roads. This pattern contrasts with the human shield hypothesis which predicts that predators avoid human activity while prey do not, using human presence as a shield against direct competitors or predators (Berger 2007; Muhly *et al.,* 2011a). Therefore, our findings align with the 'landscape of fear' framework, which suggests that non-consumptive recreational activities (e.g. hiking and four-wheel-driving) shape wildlife behaviour and habitat use through perceived risk (Frid *et al.,* 2002; Gaynor *et al.,* 2019). By mutually avoiding humans, both predator and prey may be force into greater spatial and temporal overlap, leading to increase predation and its non-consumptive effects (e.g., risk effects) (Van Scoyoc *et al.,* 2023). However, changes in return times may represent adaptive strategies with wildlife moving into adjacent habitat to cope with a disturbance. In such cases, human-altered predator–prey overlap may be temporary and unlikely to have lasting consequences for ecological communities (Van Scoyoc *et al.,* 2023). Addressing this uncertainty requires further research that integrates behavioural, physiological and demographic responses.

Our results showed that motorised activity was significantly associated with longer return times across all species and seasons, whereas non-motorised activity did not significantly influence wallaby return times during the cold season. This lack of response suggests that wallabies have higher tolerance thresholds to non-motorised recreation when overall human activity is lower, consistent with other findings that contextual factors mediate wildlife responses to disturbance (Tablado *et al.,* 2017; Smith *et al.,* 2021; Sytsma *et al.,* 2022). Nevertheless, further research involving non-observational approaches (e.g., experimental) is needed to fully characterise the conditions underlying non-response of wallabies to non-motorised activity during this season. Furthermore, the apparent reduced effect of non-motorised recreation in the cold season can be explained by that fact that during this season longer intervals between animal detections inherently contain a smaller number of recreational events (Dymit et al. 2025). In addition, grouping all forms of non-motorised activities (e.g., hiking and mountain biking) into a single category may have masked distinct effects of specific activities. For instance, some mammals have been found to perceive mountain biking more similarly to vehicles than to hikers (Naidoo *et al.,* 2020a). Future research should prioritise examining wildlife responses to these activities separately. Another future direction will be identifying road use thresholds; point at which motorised and non-motorised activity begins to cause significant impacts on wildlife (Marion *et al.,* 2002; Dertien *et al.,* 2021).

Within the context of managing PAs, our findings have important implications. If managers aim to mitigate the most harmful disturbance first, our results suggest prioritising strategies targeting motorised users, which showed to be a consistent source of perceived risk across species. This consistency likely reflects the higher speeds, louder noise emissions (Barber *et al.,* 2010; Tablado *et *al.,* 2017), and the added threat of collisions (Hobday 2010; Nguyen *et al.,* 2019) associated with vehicles. Practical measures could include enforcing clearly marked speed limits (Miller *et al.,* 2020c), and implementing seasonal restrictions during peak periods (e.g. the warm season in Tasmania) (Schummer *et al.,* 2003; Miller *et al.,* 2020c). However, seasonal restrictions, should balance human and ecological benefits and be justified with population level evidence (Miller et al., 2020; Schummer et al., 2003). At the same time, given the significant effects of non-motorised activities on wildlife, and the projected rise in visitation to many Tasmania PAs (Tasmania Parks and Wildlife Service 2024; Tourism Tasmania corporate 2024) managers should incorporate ongoing monitoring of human-use trends (Rice *et al.,* 2020). This will allow them track changes in visitation and recreational behaviour over time and adjust conservation strategies accordingly.

While our study characterises the effects of motorised and non-motorised recreation on wildlife, there are limitations to the inferences we can make. First, we focused on estimating wildlife habitat use to human activities on roads, and thus it was not possible to determine the spatial magnitude to which wildlife may be displaced from roads by anthropogenic activity. Furthermore, our model does not incorporate differences in detection rates and behavioural dynamics between species and types of recreational activity. This limitation has been shown to produce false indications of avoidance in studies using time-based approaches such as avoidance-attraction ratio (AAR) methods, which compare time intervals between species detections (Parsons et al. 2016; Dymit et al., 2025). Although our time-to-event approach differs from AAR methods by modelling time to the next detection and including the type of recreational activity as a covariate, we recommend further research using GPS or accelerometer data to account for the directionality of species movements (Dymit et al., 2025; Flowers, 2019). Satellite tracking collars on focal species would also allow to determine the spatial magnitude to which wildlife may be displaced at finer behavioural scales (Suraci *et al.,* 2020), while also enabling assessments of whether responses of wildlife vary between sex and age classes. Second, the presence of a third species between return times can introduce constraints in the observed patterns (Niedballa *et al.,* 2019; Van Scoyoc *et al.,* 2023). While one possible approach to addressing this would have been to exclude time intervals where a third species was present, this would have come at the cost of reduced sample size and thus, statistical power (Niedballa *et al.,* 2019). Finally, our framework did not account for variation in visitation levels across PAs or across years because such data was unavailable for many areas, and to maintain a robust sample size. A future study with sufficient sample sizes across PAs with contrasting human visitation levels, or across years within a single PA where visitation is monitored, could help disentangle the influence of variations on overall human visitation levels on wildlife return times.

Conclusion

In this study we illustrate how time-to-event data on wildlife and humans, collected from a large-scale camera trap survey, can help researchers and park managers test the immediate spatiotemporal responses of wildlife (e.g., return times) to recreational activities. Our findings provide evidence that both predator and prey perceive human activities in protected areas as a source of risk, offering important insights into the extent of recreational impacts on wildlife and their interactions. Given the complexity of wildlife responses to human activities, standardised methods such as camera traps can aid in the endeavour of accounting for diverse factors influencing these interactions.

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