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Drone-based wildlife surveys elicit minimal vigilance in nocturnal arboreal mammals: evidence from comparisons with ground-based detection methods

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ABSTRACT

Wildlife surveys are essential for monitoring populations, informing conservation actions, and assessing impacts of environmental change and management activities. Emerging technologies such as drones are increasingly used for habitat mapping and wildlife detection and monitoring, offering advantages, including greater survey coverage and improved detection rates, and are therefore attractive for wildlife research and conservation efforts. However, their increased application raises important animal welfare concerns, as drones may introduce novel stimuli such as noise, rotor downwash or artificial illumination that may provoke behavioural disturbance. Using over 900 thermal-infrared video recordings collected during drone surveys for nocturnal arboreal mammals in temperate *Eucalyptus* forests of south-eastern Australia, we assessed whether animals noticed the drone and exhibited behavioural changes, including those indicative of vigilance. These observations were compared with behaviour recorded during traditional ground-based spotlighting surveys. Across all species observed, behavioural responses to drone observation were minimal – only 17% of individuals appeared to notice the drone and 11% exhibited vigilant behaviour, with no evidence of flight responses. By contrast, spotlighting elicited vigilance in most animals, with individuals being over 19 times more likely to remain calm under drone observation than under spotlighting. Species-specific analyses showed that generalist species such as common ringtail possums (*Pseudocheirus peregrinus*) and brushtail possums (*Trichosurus* spp.) displayed very low vigilance during drone flights, whereas gliding and acoustically communicative species such as southern greater gliders (*Petauroides volans*) and yellow-bellied gliders (*Petaurus australis*) were more sensitive but still considerably less reactive than during spotlighting. Seasonal variation also influenced responses, with vigilance highest in autumn – often associated with breeding activity in arboreal marsupials – and lowest in spring. Our findings indicate that drone-based survey methods provide an effective and minimally invasive approach for monitoring arboreal mammals while maintaining ethical survey standards and reliable behavioural data.

Keywords: animal behaviour, arboreal mammals, drone, marsupial, thermal infrared, UAV, wildlife monitoring, wildlife survey.

Introduction

Surveys are essential for assessing and monitoring the occurrence and abundance of wildlife. They provide critical information that can inform conservation actions such as protecting habitat in areas subjected to forest management activities, including logging, or assessing the impacts of such management on local populations (Jones 2011; Lahoz-Monfort and Magrath 2021). Surveys are conducted using a range of methods, often designed to suit particular taxa or habitats. Ground-based approaches, such as transect

Collection: Marsupials in Victoria: survival in the face of current and future threats

walks or spot counts are widely used for terrestrial fauna, allowing for the detection from tracks, scats, calls and through visual sightings (Sutherland 2006). Spotlighting surveys are particularly effective for detecting nocturnal species such as arboreal mammals whose reflective eyeshine or movement can be detected under artificial light (Allison and Destefano 2006). Aerial counts (e.g. by aircraft) are commonly used for large, wide-ranging species such as ungulates, waterbirds and marine mammals, enabling coverage of extensive or inaccessible landscapes (Kingsford *et al.* 2020; Graves *et al.* 2022). More recently, emerging technologies such as thermal imaging (Croon *et al.* 1968; Vinson *et al.* 2020; Tan *et al.* 2025) and drone-based detection and monitoring have expanded survey capabilities across diverse environments, including forest ecosystems (Gonzalez *et al.* 2016; Witt *et al.* 2020; Wagner *et al.* 2025). Drone-based surveying offers new opportunities to detect species and collect high-resolution data on detection, occurrence, abundance and behaviour (Beranek *et al.* 2020; Schad and Fischer 2022; Ryan *et al.* 2025; Wagner *et al.* 2025).

Drones (also unoccupied aerial vehicles, UAV, or remotely piloted aircraft systems, RPAS) allow increased access to remote or hazardous areas, which improves our ability to monitor ecosystems or species, with little human intrusion (Singh and Frazier 2018; Witt *et al.* 2020; Schad and Fischer 2022; Wagner *et al.* 2025). In wildlife studies, drones are increasingly used to detect, count and track animals, map habitat features (Wagner *et al.* 2021*b*; Daniel Kissling *et al.* 2024), or assess population or behavioural responses to environmental change (Beranek *et al.* 2020; Ryan *et al.* 2025; Wagner *et al.* 2025). Advances in sensor technology, especially in thermal imaging, enhance their capacity to detect nocturnal species and to integrate ecological and behavioural data (Zhang *et al.* 2023). Using thermal sensors to detect an animal's heat signature does not rely on direct illumination and may therefore be less intrusive (Croon *et al.* 1968). Subsequent observations for species identification or behaviour assessments may still, however, require illumination of the animal when surveying at night (Wagner *et al.* 2025) and the drone itself may disturb the animal (Mulero-Pázmány *et al.* 2017; Schad and Fischer 2022). With the increase in drone use for ecological, and specifically wildlife, surveys, it is important to investigate potential adverse responses of wildlife to drones in order to develop best practices for drone wildlife monitoring (Hodgson and Koh 2016).

Drones operate at low altitudes, produce noise, air turbulence and rotor downwash, and may be equipped with light sources or other instruments that may cause distress to wildlife (Mulero-Pázmány *et al.* 2017; Afridi *et al.* 2025). As such, the increasing use of drones in natural environments can be seen as a form of anthropogenic disturbance (Christie *et al.* 2016; Mulero-Pázmány *et al.* 2017; Rebolo-Ifrán *et al.* 2019) that needs to be considered and potentially controlled or mitigated. Early reports of drone-induced disturbance arose from studies focused on using drones for population estimation, where researchers noticed that aversive animal reactions could compromise data quality. This recognition led to a growing body of research across many taxa investigating behavioural responses to drones (Schad and Fischer 2022). Early insights reveal that wildlife reactions to the presence of drones often depend on the type of UAV and flight attributes, as well as the characteristics of the species affected or observed (Mulero-Pázmány *et al.* 2017). Some aerial and terrestrial species are more likely to show behavioural responses than others (Rebolo-Ifrán *et al.* 2019). For example, birds may associate drones with aerial predators (McEvoy *et al.* 2016), whereas herd animals such as African ungulates may associate sounds emitted by drones with swarming bees, resulting in flight responses (Bennitt *et al.* 2019). The diversity of study designs and methodologies has, however, made systematic comparisons difficult (Mulero-Pázmány *et al.* 2017; Schad and Fischer 2022).

It is important to assess behavioural responses to drone-based wildlife detection and monitoring methods to ensure they are conducted ethically and minimise disturbance impacts. Because the application of drones for targeted wildlife surveys is still in its infancy and, in some cases experimental (Vas *et al.* 2015; Schroeder *et al.* 2020; Elmore *et al.* 2023), behavioural responses of wildlife to drone-based detection and monitoring have been scarcely reported, evaluated or studied (but see e.g. Weimerskirch *et al.* 2017; Bennitt *et al.* 2019; Ditmer *et al.* 2019). This is especially the case for nocturnal fauna, which require specialised equipment such as the combination of thermal cameras and drone-mounted searchlights (Witt *et al.* 2020; Ryan *et al.* 2025; Wagner *et al.* 2025). This highlights the need for more systematic documentation and reporting of behavioural responses in drone-based wildlife surveys. Even when wildlife surveys for research and conservation are carried out with non-invasive intentions, the act of observing wildlife can alter natural behaviours and raise animal welfare concerns (Mulero-Pázmány *et al.* 2017; Schad and Fischer 2022). Recognising and understanding these disturbances is therefore critical for refining survey techniques to balance data quality with animal welfare and ethical research practice (Beranek *et al.* 2020). Given the promising advantages of drone surveys, including increased survey area and improved detection and geolocation of individuals for threatened species monitoring and conservation (Zhang *et al.* 2023; Ryan *et al.* 2025; Wagner *et al.* 2025), a clearer understanding of the potential impacts is required.

Study aims and objectives

This study used high-resolution video footage of arboreal mammals and associated fauna, collected during thermal drone surveys designed to evaluate detection performance relative to spotlighting (Wagner *et al.* 2025), to assess behavioural responses of nocturnal arboreal wildlife in native eucalypt forests of south-eastern Australia to drones under

operational survey conditions. We contrast reactions and behaviours with a commonly used ground survey method – spotlighting on foot – for the same set of nocturnal arboreal species. Although spotlighting is especially effective in detecting nocturnal arboreal and ground-dwelling mammals or birds (Chick *et al.* 2020; Cripps *et al.* 2021), the use of bright spotlights can disrupt natural behaviours and cause increased vigilance and physiological stress (Dimovski *et al.* 2025). Given known reactions to observation by spotlighting of arboreal fauna occupying temperate eucalypt forests, we hypothesised that: (1) vigilance responses of nocturnal arboreal mammals in response to observation by drones are less common, and (2) that arboreal mammals will show lower rates of vigilant behavioural reactions to drones compared with spotlighting surveys.

Methods

Study area, species and data inclusion

Data on behavioural responses of arboreal fauna to observation were collected during drone and spotlighting surveys in the temperate *Eucalyptus* forests of Victoria, south-eastern Australia, between 2018 and 2024. Initial drone surveys were carried out as part of a research project looking into the efficacy of using thermal drones to detect nocturnal arboreal fauna (see Wagner *et al.* 2025) and were complemented by additional drone surveys designed to assess legacy effects of forest management on arboreal fauna populations (B. Wagner, S. W. Garnick, M. F. Ryan, C. R. Nitschke and R. Trouve, unpubl. data). Surveys were predominantly conducted in the Central Highlands region, to the east of Melbourne and in and around Wombat State Forest, west of Melbourne, with some additional surveys carried out in the Gippsland and East Gippsland regions in eastern Victoria (Fig. S1 of the Supplementary material). Thermal video footage was collected primarily for species identification and subsequent occupancy and abundance analyses; however, for this study, the footage was reviewed in full to allow a consistent *post hoc* assessment of animal behaviour (see below).

Spotlighting was conducted for research projects focused on detecting the southern greater glider (*Petauroides volans*), but all detected arboreal species were recorded while surveying. Survey results included in this study were initially collected to conduct habitat suitability modelling in the Central Highlands and East Gippsland (Wagner *et al.* 2020), map foraging habitat in mixed-species eucalypt forests in East Gippsland (Wagner *et al.* 2021*a*, 2021*b*) and determine the effects of the 2019–20 Black Summer bushfires on tree hollows for cavity-nesting arboreal fauna in eastern Victoria (Wagner *et al.* 2024; Fig. S1). Additional spotlighting surveys were conducted in the same areas and within the same survey footprint as those that were surveyed by drone in Wagner *et al.* (2025).

The focus species for all surveys were nocturnal arboreal mammals of south-eastern Australia (Table 1). Drone surveys generally detected more species than spotlighting surveys (Wagner *et al.* 2025), including terrestrial mammals. Drone surveys also detected nocturnal bird species as well as diurnal birds (observed sleeping or resting). Both spotlighting and drone surveys detected non-native species (Table 1).

Although drone and spotlighting data originated from several independent research projects, survey methods were largely standardised. All drone surveys followed the same operational protocol described in Wagner *et al.* (2025) and below. Spotlighting survey observations were included only if they used double observer distance sampling methods following Cripps *et al.* (2021) and Chick *et al.* (2020). Surveys that did not conform to these protocols or lacked complete behavioural records were excluded. As a result, analyses were restricted to datasets collected under consistent field methods, ensuring comparability across surveys. Because our behavioural analyses focused on transitions relative to detection rather than abundance or density estimation, we did not include project or site level random effects.

Drone survey methods and capturing video footage

Drone surveys were conducted using DJI Matrice 300/350 or M30T multirotor drones (DJI, Shenzhen, China). A thermal-infrared camera was used to detect animal heat signatures while the drone was manually flown to follow a boustrophedon pattern, covering an area of 100–200 ha at 10–30-m altitude above the forest canopy (tree height averages ranged from 30 to 60 m, depending on forest type), leading to a flight altitude between 40 and 90 m above ground level. When a thermal signature was detected, the drone was flown closer to the animal by decreasing the altitude to allow capturing higher quality footage. The drone remained a minimum of 10-m perpendicular distance (as measured by the sensor's laser range finder) from the observed individual. The drone's approach angle towards the detected thermal signature depended on tree height and density, but whenever possible, the drone first descended vertically, then approached the observation horizontally. In many cases the drone remained above the individual, tilting the camera and searchlight to capture video footage. We used a bright drone-mounted searchlight and the thermal camera's secondary zoom lens to record video footage for identifying species and assessing behaviour. The searchlight was turned on when the drone had been flown into position near the individual. We used DJI Zenmuse S1 and CZI GL60 Plus (CZI, Gunangzhou, China) searchlights on DJI Matrice 300/350 drones and the CZI GL60 Mini on the M30T. As these searchlight models have different specifications, all lights were set to operate at ~2000 lm using a Protech Pro 400k digital lux meter at night, tested at a distance of 10 m from the light. Brightness also depended on distance to

Table 1. Species detected during spotlighting and drone-based thermal surveys for this study.

Common name	Scientific name	Nocturnal or diurnal	Native or introduced
Arboreal mammals			
Common brushtail possum	*Trichosurus vulpecula*	Both	Native
Common ringtail possum	*Pseudocheirus peregrinus*	Both	Native
Eastern pygmy possum	*Cercartetus nanus*	Nocturnal	Native
Feathertail glider	*Acrobates pygmaeus*	Nocturnal	Native
Koala	*Phascolarctos cinereus*	Both	Native
Krefft's glider	*Petaurus notatus*	Nocturnal	Native
Leadbeater's possum	*Gymnobelideus leadbeateri*	Nocturnal	Native
Mountain brushtail possum	*Trichosurus cunninghami*	Both	Native
Southern greater glider	*Petauroides volans*	Nocturnal	Native
Yellow-bellied glider	*Petaurus australis*	Nocturnal	Native
Terrestrial mammals			
Bare-nosed wombat	*Vombatus ursinus*	Both	Native
Short-beaked echidna	*Tachyglossus aculeatus*	Both	Native
Eastern grey kangaroo	*Macropus giganteus*	Diurnal	Native
Long-nosed bandicoot	*Perameles nasuta*	Nocturnal	Native
Swamp wallaby	*Wallabia bicolor*	Both	Native
Birds			
Southern boobook	*Ninox boobook*	Nocturnal	Native
Tawny frogmouth	*Podargus strigoides*	Nocturnal	Native
Australian magpie	*Gymnorhina tibicen*	Diurnal	Native
Pied currawong	*Strepera graculina*	Diurnal	Native
Superb lyrebird	*Menura novaehollandiae*	Diurnal	Native
Wedge-tailed eagle	*Aquila audax*	Diurnal	Native
White-winged chough	*Corcorax melanorhamphos*	Diurnal	Native
Introduced species			
Cat	*Felis catus*	Both	Introduced
Dog	*Canis familiaris*	Both	Introduced
Red fox	*Vulpes vulpes*	Nocturnal	Introduced
Sambar deer	*Rusa unicolor*	Both	Introduced

Any observations of strictly diurnal species were not assessed in this study.

the observed individual or object. Animals were exposed to the searchlight only for the time required to capture sufficient footage for identification by a trained wildlife ecologist. The drone then returned to flight altitude of 10–30 m above the canopy to continue the survey. A maximum of 1 min of video footage capture was planned; however, longer observation periods were required in some cases to obtain clear footage or when multiple individuals or species were present in the same tree or vicinity. Average video clip length was 42 s, with durations exceeding 60 s in 72 cases (7% of all observations). The laser range finder of the thermal camera was used to record the animal's location. Observations from 86 drone surveys were used to assess animal behaviour in response to being observed by drone. Reviewed animal footage ranged from 1 to 88 video files per survey, with an average of 12 video files per survey.

Spotlighting survey methods

Spotlighting surveys were conducted using double observer distance sampling methods to maximise animal detection of nocturnal arboreal mammals (see Cripps *et al.* 2021).

Surveys were either conducted on 500-m transects through the forest or 1000-m transects along a forest track or road. Two observers conducted independent surveys, walking ~10 min apart while using strong torchlights (Olight Javelot Pro, Olight, Zhongshan, China, or equivalent with narrow field of view, up to 2500 lm) to scan the forest canopy for eyeshine reflection of arboreal fauna (Chick *et al.* 2020). When eyeshine was detected, binoculars were used to identify the species, and a laser range finder and compass were used to record distance and bearing to the animal for subsequent abundance calculations. The observer also recorded information on the tree species the animal was observed in, fur colour and behaviour (see below). To minimise animal disturbance and in accordance with animal ethics approvals, spotlighted individuals were only observed for the period of time required to identify both species and initial behaviour (generally 1–5 min). Behavioural observations from 133 spotlighting surveys were considered for this analysis. The number of individual observations per survey ranged from 1 to 43 animals. To ensure independence of behavioural observations, we retained only detections that were unique to a single observer. Observations made by the second observer were excluded when they involved an individual that had already been detected by the first observer, thereby minimising potential behavioural carry-over effects arising from initial detection and observation.

Interpretation of animal behaviour

Drone surveys

The behaviour of animals observed by thermal drone was assessed *post hoc* by three trained wildlife ecologists (including authors B. Wagner and J. Johnson), who independently reviewed all recorded thermal video footage in an office setting at normal playback speed. Each assessor used a pre-formatted spreadsheet to record species, clip length, behaviour and behavioural change. Expected behaviours were pre-categorised (see below), and assessors selected categories from a drop-down menu to standardise classifications across assessors. For each video clip, the length in seconds was noted, and any clips shorter than 10 s were removed as they did not allow enough time to determine behaviours or whether the animal noticed the drone or changed behaviour in response to being observed. Longer clips that included multiple animal observations or species were split into several shorter clips to assess each individual's response separately. A total of 987 video clips longer than 10 s were reviewed. The reviewer identified and noted the species in a clip. Any clips where species could not be identified or the species were identified to be non-nocturnal fauna (e.g. diurnal birds, Table 1) were removed from further assessment. We determined if the observed animal noticed the drone, if a behavioural change occurred, and classified which behaviour was exhibited at the start of each video (i.e. initial behaviour) and any subsequent behaviour (i.e. either after noticing the drone or without noticing the drone). The three independent assessments were compared and in cases where reviewers differed in their interpretation of animal response or behaviour, footage was re-assessed. Reviewers then discussed their observations to resolve discrepancies and reach consensus, resulting in a final agreed assessment for each individual animal's response and behaviour.

We classified an animal as 'noticing the drone' when it visibly looked up toward the drone camera and searchlight. In the video footage, this was often identifiable by a distinct eyeshine reflection, which indicated that the animal had directed its gaze into the light source. However, cases occurred where eyeshine was visible, but the animal was clearly not looking at the camera, so careful review and replay of each clip was required. To allow consistent interpretation of observed activities, we categorised behaviours into a set of classes commonly expressed by nocturnal arboreal fauna: 'feeding', 'frozen' (remaining still while staring at the camera, a behaviour also frequently documented during spotlighting surveys; see below), 'idle/looking away', 'looking at the camera', 'moving' and 'other' (e.g. social interactions, grooming). For subsequent analyses, we further simplified these behavioural categories into two functional groups. Specifically, 'looking at the camera' and 'frozen' were classified as 'vigilant' behaviours (Fig. 1). This was based on the assumption that these behaviours reflected a reaction to the drone's presence and represented a transition away from calm behaviours toward a potential vigilance or stress response (Colombelli-Négrel *et al.* 2023). As such, for the purpose of this study, we based our definition of 'vigilance' on koala observations by Colombelli-Négrel *et al.* (2023), describing an erect or tense posture with body and ears directed toward the potential disturbance (Table 2). Such vigilant responses were interpreted as preventing animals from continuing typical nocturnal activities such as feeding, moving or observing their environment and hence having a potential negative effect on the individual.

A change in behaviour was recorded for any animal if a transition from one behavioural category to another was observed during the period covered by video footage, regardless of whether the animal noticed the drone or not. This measure was coded as either 'Yes' (change observed) or 'No' (no change observed). To capture a sequence of activities, up to three behaviours were documented per observation: the first represented the initial behaviour at the start of the video clip, whereas the second (and, where applicable, third) reflected subsequent behaviours expressed later in the same recording.

Spotlighting surveys

Spotlighting surveys were conducted by trained wildlife ecologists with extensive knowledge of the ecology and behaviour of the focal species. Once an individual was

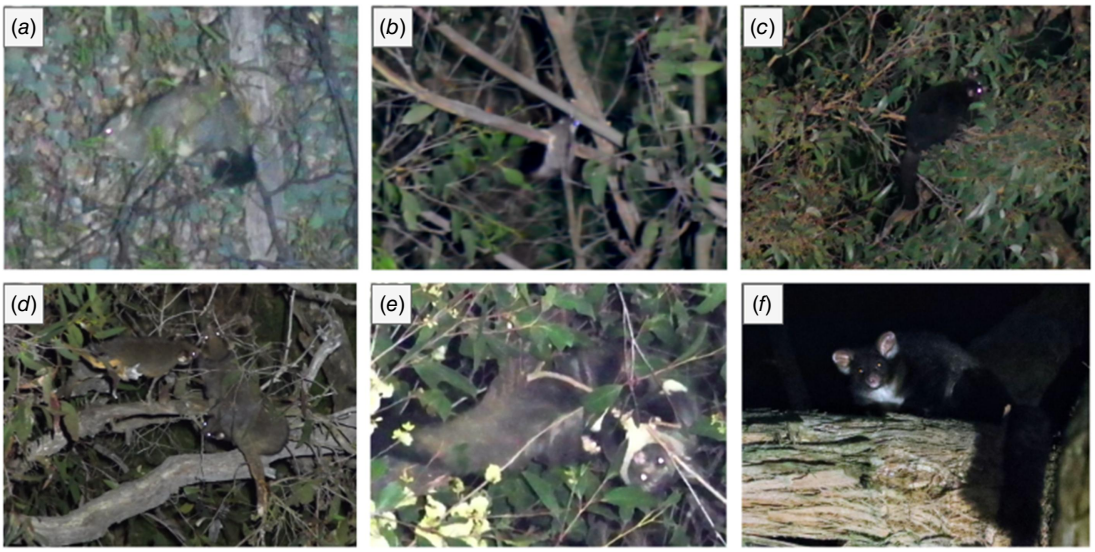

Fig. 1. Stills from analysed video clips captured by drone (*a–e*), illustrating classified behaviours and the typical behavioural response of arboreal mammals when observed from the ground by spotlighting (*f*). (*a*) Common brushtail possum (*Trichosurus vulpecula*, with joey on its back) reaching for branch and feeding on leaves and flowers – classified as 'feeding'. (*b*) Leadbeater's possum (*Gymnobelideus leadbeateri*) about to leap from one branch to another – classified as 'moving'. (*c*) Southern greater glider (*Petauroides volans*) sitting idle in a crown, not noticing drone – classified as 'looking away'. (*d*) Common ringtail possums (*Pseudocheirus peregrinus*), likely a family group, grooming and socialising – classified as 'other'. (*e*) Yellow-bellied glider (*Petaurus australis*) looking towards the drone and subsequently stopping its initial grooming behaviour – classified as 'notices the drone', then 'looking at the camera' and then 'vigilant'. The video footage illustrating these behaviours can be viewed in the 'Video examples of animal detections and behaviours observed by thermal drone' section of the Supplementary material. (*f*) Shows a southern greater glider photographed after detection during spotlighting surveys. The animal kept staring at the observer for the duration of relevant data collection and was hence classified as 'vigilant'.

Table 2. Ethogram of animal behaviours in this study.

Behaviour	Description	Reference(s)
Feeding	Actively consuming or smelling food such as leaves, flowers, buds, sap or bark	Adam *et al.* (2021) and B. Wagner, pers. obs.
Looking	Animal has its head raised, eyes open and moves head to look at environment or is resting with eyes open but sitting motionless, not looking towards disturbance source	Colombelli-Négrel *et al.* (2023)
Moving	Locomotion in canopy, including climbing, jumping from branch to branch or gliding between trees	Adam *et al.* (2021) and B. Wagner, pers. obs.
Vigilant	Erect or tense posture, body and ears directed towards the disturbance source, staring into light source without further movement	Colombelli-Négrel *et al.* (2023), B. Wagner and J. Johnson, pers. obs.
Other	Included behaviours such as social interactions with other individuals or offspring, grooming, socialising	B. Wagner and J. Johnson, pers. obs.

located, its behaviour was recorded *in situ* using binoculars, while the torchlight was directed at the animal. Behavioural observations were made after the species was confidently identified, ensuring that species determination did not interfere with behavioural classification. On the field datasheets, the 'behaviour' section provided space for free-text notes but required the observer to record whether the animal appeared 'frozen' (i.e. immobile, with eyes directed towards the spotlight, a behaviour frequently observed during these surveys). Standardised behavioural categories included 'feeding', 'looking', 'moving' and 'other'. However, observers frequently documented more specific behaviours, such as 'gliding', 'resting', 'hiding in a hollow', 'staring at the observer' or 'active'.

For consistency with drone footage assessments, these behaviours were reclassified into the same broader categories. As such, 'gliding' was recoded as 'moving', 'resting' or 'sitting' as 'idle/looking away', and observations such as 'staring at observer', 'watching observer' or 'hiding in a hollow' were grouped as 'vigilant', alongside 'frozen'. This

ensured comparability across methods despite differences in data collection approaches.

As animals observed by spotlighting were not subjected to prolonged exposure to the concentrated torchlight beam, only the first behaviour upon detection was recorded. No subsequent behavioural transitions were documented during spotlighting surveys, in contrast to drone-based observations where continuous footage allowed longer-term observations. A total of 579 animal observations from spotlighting were included in the analysis.

Data analysis

We quantified the proportion of animals that showed evidence of noticing the drone and classified their final recorded behaviours. These data were then used to construct alluvial plots, which illustrated and allowed to explore the flow of behaviours from initial to subsequent observations. This approach allowed identifying how often vigilant responses occurred, as well as the behavioural states from which these responses originated. To complement this descriptive analysis, we calculated transition probabilities between behavioural states. These were derived both across all observations and for the subset of animals that visibly noticed the drone. This enabled an assessment of the overall likelihood of behavioural change and how detection of the drone influenced the direction and frequency of transitions between calm and vigilant behaviours. Owing to the applied nature of the data, our aim was to evaluate behavioural responses under operational, real world survey conditions. Hence, we could not standardise observation duration, illumination time or the distance at which animals were first detected. These factors vary naturally across applied drone-based fauna surveys due to differences in environmental conditions, canopy structure, drone models and species encountered. Accordingly, analyses focused on behavioural transitions relative to the moment of first detection rather than controlled flight-initiation metrics, aligning with the objective of assessing behaviour as it occurs during routine monitoring.

As drone surveys were carried out over more than 12 months, we also derived transition probabilities for each season, sub-setting the dataset into (southern hemisphere) summer (December, January, February), autumn (March, April, May), winter (June, July, August) and spring (September, October, November). We then tested for significant differences in the occurrence of vigilant or calm behaviours using a binomial generalised linear model (GLM) with behaviour ('vigilant' = 1, 'calm = 0) as response and season as a factorial explanatory variable. We evaluated these models using Tukey Honest Significance (HSD) tests for pairwise comparisons. We were specifically interested to compare other seasons against autumn, given many arboreal mammals are breeding during or around this season.

To compare behavioural responses between the drone and spotlighting surveys, we simplified both datasets into one behavioural observation per observed individual. In the drone dataset, we retained 'vigilant' if any of the three observed behaviours was noted as 'vigilant'. We then also categorised all other behaviours in both datasets as 'calm' and coded the variable binomial ('vigilant' = 1, 'calm' = 0). Before conducting further analyses, we used drone observation data only to determine if the length of observation significantly affected the likelihood of observing vigilant behaviour using a binomial generalised linear model (GLM). Clip length was not significant ($P = 0.313$) and the probability of a vigilant response due to clip length was close to the baseline probability as determined by the model intercept (14.4 and 13.7% respectively). This indicated that we could retain all drone observations (>10 s) regardless of video clip length for further analyses.

We conducted both survey method-specific (drone and spotlighting observations considered separately) and combined statistical tests to evaluate proportional behavioural responses. For method-specific analyses, we applied Pearson's Chi-Square tests to contingency tables that categorised behaviours as either vigilant or calm. We used Chi-Square tests to assess whether there was a significant association by comparing the observed counts in each category to the counts expected if there were no association. These tests quantify the statistical significance of deviations from equal proportions, and Chi-Square statistics, which provide a measure of the magnitude of those deviations. For the combined dataset (comparison of drone and spotlighting observations), we constructed contingency tables separating vigilant from calm behaviours by survey type. Here, we used Pearson's Chi-Square tests together with effect size measures to capture whether significant differences existed and how strong these associations were. We used *P*-values to assess statistical significance, odds ratios (with confidence intervals using a 0.95 confidence level threshold) to quantify the relative likelihood of vigilant behaviours between methods, and Cramer's *V* as a standardised measure of association strength between survey method and behavioural outcome.

Finally, we fitted a GLM with behavioural outcome ('vigilant' *v*. 'calm') as the response variable and the interaction between survey method and species as predictors. This approach allowed us to determine whether particular species were more likely to exhibit a vigilant reaction under either drone or spotlighting surveys, while accounting for differences in response patterns among species. Only species with sufficient sample sizes (at least 20 observations in each survey type) were included in the analysis to ensure reliable model estimates; these were: brushtail possum(s), common ringtail possum, Krefft's glider, southern greater glider and yellow-bellied glider. From this model, we derived specific *P*-values for assessing significance and probabilities of exhibiting a vigilant response under each survey method by species, allowing comparison of behavioural sensitivity within and between methods. Additionally, we calculated odds ratios with 95% confidence intervals using pairwise

comparisons to quantify the relative likelihood of vigilant behaviour under drone *v*. spotlighting surveys.

Results

Observed behaviours and responses to being observed

Drone surveys

We recorded most animals' initial behaviour (behaviour exhibited at the start of each video clip) as 'looking away' and 'feeding'; 48% of all individuals were 'looking away' (not at the camera, $n = 469$), whereas 28% were 'feeding' ($n = 273$) and 19% were 'moving' ($n = 190$). Only in 42 cases (4%) did the individual animal show an immediate initial vigilant behaviour; 17.4% of animals ($n = 172$) visibly noticed the drone by looking towards the camera. Subsequently, 11.2% of individuals ($n = 111$) showed a vigilant behaviour by freezing or not exhibiting any calm behaviours while being observed, and 40% kept looking away ($n = 396$), 25% were feeding ($n = 250$) and 22% were moving ($n = 219$, Fig. 2). Around 1% of all observations exhibited 'other' behaviours both initially and subsequently ($n = 13$). We did not record any flight behaviour in response to drone observation. Any movement behaviour that occurred after an animal noticed the drone was considered 'calm'.

Spotlighting surveys

Behaviours observed during spotlighting surveys were classified as 'vigilant' for 77% of individuals ($n = 443$, Fig. S2 of the Supplementary material). 17% ($n = 97$) kept moving, whereas 6% were either feeding or exhibiting other behaviours ($n = 37$). Only two animals that were observed by spotlighting were recorded as 'looking away'.

Transition of behaviours while being observed by drone

When all drone observations were considered, including individuals that did not notice the drone or exhibit any behavioural response to the drone, transition probability analysis indicated high behavioural consistency across observation intervals. The likelihood of individuals maintaining their initial behaviour was greatest for 'feeding' (83%), 'moving' (88%) and 'looking away' (76%), whereas 'other' behaviours had moderate persistence (54%). The highest probabilities for transitions from calm to vigilant were recorded for transitions from 'looking away' (14%) and 'feeding' (10%) to 'vigilant'. Individuals already exhibiting vigilant behaviours were most likely to remain in that state (26%) or transitioned to looking away (45%, Fig. 3*a*).

When considering only individuals that appeared to notice the drone (17% of all observations; $n = 172$), transition probabilities indicated a higher frequency of vigilant responses. Animals initially exhibiting calm behaviours such as 'feeding' (87%), 'looking away' (77%) or 'moving' (50%) frequently transitioned to 'vigilant' states, and those initially classified as 'other' did so in all cases. Conversely, persistence of calm behaviours was low, with probabilities of maintaining 'feeding' (13%), 'looking' (2%) or 'moving' (29%) substantially reduced compared to the full dataset. Individuals that initially displayed 'vigilant' behaviours transitioned to 'looking away' in 45% of cases or 'moving' in 17% of cases, whereas 26% of cases maintained a 'vigilant' state (Fig. 3*b*).

Seasonal differences in behavioural responses and transitions

When analysing behaviour by season, spring and winter had a lower probability of vigilant behaviour compared to autumn, whereas summer did not differ significantly from autumn ($P = 0.545$). Autumn had the highest probability of vigilant behaviour (25%), whereas spring had the lowest (9%, see Table S1 of the Supplementary material). Spring consistently had the lowest vigilant behaviour rates, and autumn the highest (Fig. S3 of the Supplementary material). Pairwise comparisons revealed vigilant behaviour was 3.5 times more likely in autumn compared to spring. Spring also showed significantly lower vigilant behaviours compared to summer and winter, whereas the comparisons between autumn, summer and winter, as well as summer and winter, did not reveal significant differences in behaviours (Table S2 of the Supplementary material).

Likelihood of exhibiting vigilant behaviours by survey type

Individual Chi-Square tests conducted on contingency tables revealed that the distribution of observations in both survey types deviated substantially from equal proportions. For drone observations, only 14% of animals ($n = 142$) exhibited 'vigilant' behaviour at any time while being observed, whereas the majority maintained calm behaviours. The Chi-Square statistic ($\chi^2 = 500.72$, $P < 0.001$) provided strong evidence to reject the null hypothesis of equal distribution between 'vigilant' and 'calm' behaviours. Hence, under drone surveys, animals predominantly continued their normal activities. For spotlighting observations, most animals (76%, $n = 443$) exhibited 'vigilant' behaviour, whereas only approximately one-quarter (24%, $n = 136$) displayed 'calm' behaviours. The Chi-Square test ($\chi^2 = 162.78$, $P < 0.001$) indicated that 'vigilant' behaviours predominated during spotlighting surveys.

When both drone and spotlighting observations were combined, contingency table analysis revealed a strong association between survey method and behavioural response. Chi-Square tests confirmed that proportional differences described above were highly significant (Pearson $\chi^2 = 625.32$, $P < 0.001$; likelihood ratio $\chi^2 = 601.84$, $P < 0.001$). Measures of

association indicated a strong relationship between survey method and behaviour (Phi = 0.62; Cramer's V = 0.62). Odds-ratio (OR) analysis showed that animals were approximately 19.3 times more likely to exhibit 'calm' behaviour during drone surveys compared to spotlighting surveys (95% CI: 14.91–25.18).

Species-specific responses

Species-specific binomial generalised linear models (GLMs), which included the interaction between survey method and species, revealed that the likelihood of exhibiting 'vigilant' behaviour varied markedly across species but was consistently

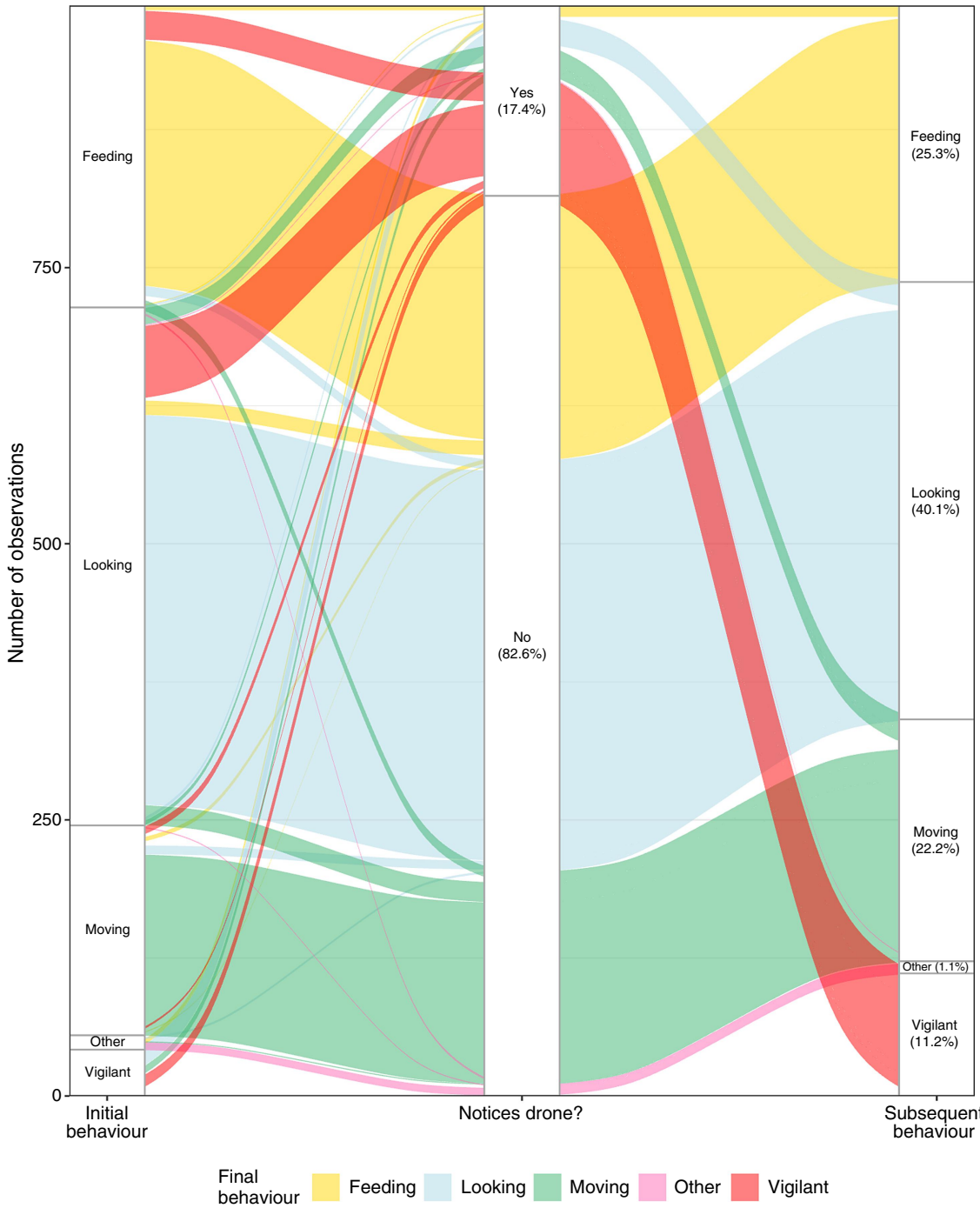

Fig. 2. Alluvial graph illustrating observed behaviours during drone surveys and behavioural change. Percentages shown for noticing the drone and final or subsequent behaviour are fractions of total number of observations (N = 987). Colours are based on the final (last) behaviour exhibited during each assessed video clip.

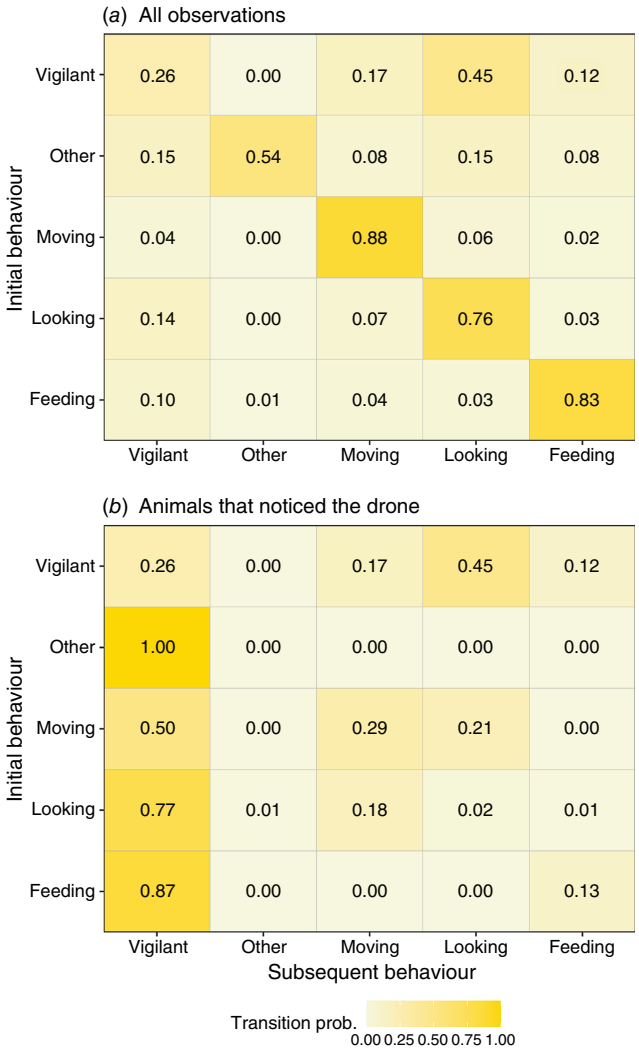

Fig. 3. Transition probabilities between initial and subsequent behaviours observed by drone for all observations (*a*, *N* = 987) and for animals that noticed the drone (*b*, *N* = 172).

lower during drone surveys. Brushtail possums were highly unlikely to show 'vigilant' behaviour to drones compared with spotlighting (OR = 0.02, $P < 0.001$). Similarly, common ringtail possums (OR = 0.045, $P < 0.001$), Krefft's gliders (OR = 0.13, $P < 0.001$), southern greater gliders (OR = 0.1, $P < 0.001$) and yellow-bellied gliders (OR = 0.04, $P = 0.004$) all exhibited substantially lower odds of vigilant reactions during drone surveys relative to spotlighting. Species-specific analyses highlighted that drones elicited substantially fewer vigilant behaviours across all focal nocturnal arboreal mammals compared with spotlighting surveys. Common ringtail and brushtail possums exhibited vigilant behaviours in 5–7% of drone observations, but showed 55–80% vigilant responses during spotlighting. Gliding species were slightly more sensitive, with 25–35% showing vigilant responses to drones. This was, however, considerably lower than 72–93% observed during spotlighting (Table 3).

Discussion

Responses of animals to observation by drone

We present an assessment of the behavioural responses and potential impacts of drone surveys on multiple nocturnal arboreal marsupials and some associated terrestrial forest fauna of south-eastern Australia, including endangered species such the southern greater glider (*Petauroides volans*) and the Leadbeater's possum (*Gymnobelideus leadbeateri*). Overall, we recorded few instances of the targeted species visibly noticing the drone and even fewer exhibiting vigilant behaviour in response to the survey drone flying nearby or overhead. Although ~17% of individuals noticed the drone, only ~11% exhibited subsequent vigilance and therefore potentially adverse responses. Analysing over 900 video clips of individual animals observed by drone, we found only a few instances of animals noticing the drone, then changing their behaviour (Figs 2, 3). In no instance were these interpreted as flight behaviour, indicating that, although some animals responded with increased vigilance, the drone may not have been perceived as a direct threat (Ditmer *et al.* 2015; Mulero-Pázmány *et al.* 2017; Colombelli-Négrel *et al.* 2023).

The response of wildlife to drone activity greatly depends on aircraft properties, flight patterns and altitude, and the type of animal being observed (Mulero-Pázmány *et al.* 2017). Species- or population-specific predation pressures can play an important role in determining whether drones or drone activity may be perceived as a threat and therefore elicit vigilant or adverse behaviours (McEvoy *et al.* 2016; Schad and Fischer 2022). Larger mammals that frequently occur in groups or herds are more likely to show increased vigilance, stress or flight reactions in response to drone surveys (Bennitt *et al.* 2019; Brunton *et al.* 2019; Schroeder *et al.* 2020). Flight behaviour in particular is likely to spread within large animal groups and negatively affect more individuals over time (Vas *et al.* 2015; Weimerskirch *et al.* 2017; Schroeder and Panebianco 2021).

Although no assessments have previously been conducted on many of the species observed in our study, research into wildlife with similar ecology, morphology, social structures, behaviours or life cycles has reported that drones seem to cause little disturbance to forest-dependent species (Mulero-Pázmány *et al.* 2017; Rebolo-Ifrán *et al.* 2019). For example, spectacled flying foxes (*Pteropus conspicillatus*) roosting in tree canopies showed only minimal disturbance responses to drone surveys used to conduct population estimates (Norris 2025). Similarly, Javan langurs (*Trachypithecus auratus*) were found to have low sensitivity to the presence of survey drones (Rahman *et al.* 2021). In many studies, increasing flight altitude reduced the likelihood of vigilant responses (Mulero-Pázmány *et al.* 2017; Schroeder *et al.* 2020). Larger, solitary species such as (captive) American black bears (*Ursus americanus*) were found to show only limited

Table 3. Predicted probabilities of vigilant behaviour by species and survey method.

Species	Survey method	Probability of vigilant behaviour	s.e.	95% CI lower	95% CI upper
Brushtail possums (*Trichosurus vulpecula* & *T. cunninghami*)	Drone	0.074	0.022	0.042	0.13
	Spotlighting	0.8	0.037	0.719	0.864
Common ringtail possum (*Pseudocheirus peregrinus*)	Drone	0.05	0.013	0.033	0.086
	Spotlighting	0.558	0.054	0.452	0.66
Krefft's glider (*Petaurus notatus*)	Drone	0.246	0.053	0.157	0.365
	Spotlighting	0.71	0.04	0.55	0.84
Southern greater glider (*Petauroides volans*)	Drone	0.289	0.028	0.235	0.35
	Spotlighting	0.79	0.024	0.73	0.84
Yellow-bellied glider (*Petaurus australis*)	Drone	0.35	0.1	0.177	0.574
	Spotlighting	0.93	0.065	0.648	0.99

Only species with at least 20 observations per survey method were considered for this analysis. Brushtail possum species were combined to reach the required sample size.

behavioural responses to drone surveys (Ditmer *et al.* 2015) and also become habituated to drone exposure over time (Ditmer *et al.* 2019). The only species included in our study that was previously assessed for their response to drone activity is the koala (*Phascolarctos cinereus*), which, in a captive environment, showed vigilance but no physiological responses to drones being flown 15 m above individuals (Colombelli-Négrel *et al.* 2023). While establishing drone survey protocols for koalas in the wild, Beranek *et al.* (2020) did not report aggressive behaviour, with koalas typically maintaining their position in the canopy while the drone was flying overhead, whereas other arboreal species, such as brushtail possums, tended to move away. Interestingly, koalas in enclosures with more canopy cover had the shortest vigilance time (Colombelli-Négrel *et al.* 2023).

Given the findings from previous research on forest-dependent fauna, we hypothesised that drone surveys would have little effect on arboreal and associated forest wildlife in temperate eucalypt forests of south-eastern Australia. The targeted arboreal species (Table 1) are solitary throughout most of the year (Henry 1984) or seasonally occur in mating pairs or small family groups, but never in large groups (Goldingay 2000, 2025). Main predators are avian (forest owls) or for some, terrestrial (introduced predator such as dogs, cats or foxes); most species (except koalas) nest in tree hollows (Gibbons and Lindenmayer 2002; Goldingay 2011), where they are protected from predation throughout the day (Gibbons and Lindenmayer 2002). It remains unclear, if animals exhibited vigilant reactions due to a perceived predator, the drone noise or the searchlight beam, or a combination of factors, which should be further investigated in future research.

Seasonal differences in responses to observation by drone

Behavioural responses varied across seasons. Although the likelihood of a vigilant behaviour response was still <25% in any season, autumn showed the highest probability of vigilant behaviour (~25%) and spring the lowest (9%, Table S1). While there are known differences in vigilance by factors such as age, sex or habitat type (Stankowich and Blumstein 2005; Tablado and Jenni 2017), our results support the importance of a seasonal effect, with implications for survey design and effort. Increased or decreased vigilance in certain seasons may reflect seasonal variation in animal activity, energetic condition or breeding status (Kavanagh 1984; Xia *et al.* 2011; Zhang *et al.* 2021; Gracanin and Mikac 2022).

Autumn coincides with breeding and post-breeding periods for many of the arboreal species observed (Goldingay 2000; Jackson and Groves 2015). The elevated vigilance observed during this period may therefore be associated with seasonal shifts in reproductive behaviour, such as mate finding or guarding, increased energetic demands or changes in perceived predation risk linked to reproductive state and heightened nocturnal activity. These mechanisms have not been explicitly examined in the context of drone surveys of arboreal mammals and thus remain speculative in this study. However, increased vigilance in response to drone surveys during breeding seasons has been reported in other taxa, such as seals (Pomeroy *et al.* 2015). More broadly, vigilance has been shown to correlate with reproductive seasons across a range of mammals (Beauchamp *et al.* 2021), where it is thought to facilitate monitoring of rivals and breeding competitors, particularly in forest-dependent species (Hirsch 2002).

Conversely, the lowest probability of vigilant behaviour observed in spring may reflect a combination of ecological and methodological factors. Spring coincides with birthing and parental care for many arboreal mammals (Clauss *et al.* 2020; García-Casimiro and Santos-Moreno 2024). Individuals – particularly females with pouch young – may spend more time sheltering in tree hollows or dens (Gibbons and Lindenmayer 2002; Selonen *et al.* 2016; Goldingay 2022), thereby reducing time spent moving or foraging in the open canopy and potentially reducing the likelihood of reacting to external stimuli such as the drone flying overhead. Increased food availability and denser canopy foliage due to leaf flush during spring may further lower energetic stress (Youngentob *et al.* 2011; Wallis *et al.* 2012) and may reduce threat perception, resulting in reduced vigilance (see e.g. Colombelli-Négrel *et al.* 2023).

As we detected statistically significant seasonal differences in vigilance, our findings highlight the importance of accounting for seasonality when planning drone surveys for arboreal fauna in south-eastern Australian eucalypt forest to minimise potential disturbances and ensure ethical wildlife monitoring practices (Hodgson and Koh 2016). Unfortunately, the study design did not allow us to determine the underlying mechanisms driving these patterns or to attribute them directly to reproductive state or seasonal ecological conditions. Species-specific temporal sensitivities need to be further explored, especially for species with conservation concern that will likely be subject to increased drone monitoring in the future (Howell *et al.* 2021; Ryan *et al.* 2025; Wagner *et al.* 2025).

Contrasting survey types and species-specific responses

Our results indicated a contrast in behavioural responses between drone and traditional ground surveys by spotlighting on foot. Under drone observations, most animals (86%) maintained common, calm behaviours, whereas spotlighting elicited predominantly vigilant responses (77% of all observations). This suggests that, in comparison, drone-based survey methods are substantially less intrusive and may allow animals to continue their normal nocturnal activities. This is reinforced by the statistical association between survey type and behavioural response, as well as high odds ratios indicating that observed animals were over 19 times more likely to exhibit non-vigilant behaviours during drone surveys, compared to ground surveys by spotlighting.

Species-specific analyses revealed that the reduced disturbance associated with drones was consistent across nocturnal arboreal mammals observed (Table 3), whereas the magnitude of responses varied among species. Generalist species such as brushtail- and common ringtail possums exhibited very low levels of vigilance during drone surveys, but displayed pronounced vigilance under spotlighting. Gliding species, including the endangered southern greater glider, were somewhat more sensitive to drone observation, with 25–35% of individuals showing vigilance to drones. This was, however, still lower when compared with 72–89% of vigilant response during spotlighting.

Our findings are consistent with previous studies showing that visual and auditory stimuli from ground-based surveying or human presence can trigger heightened alertness or even flight responses in mammals, which may be related to increases in perceived predation risk or the presence of competitors (Stankowich and Blumstein 2005; Tablado and Jenni 2017; Rahman *et al.* 2021; Norris 2025). The comparatively muted response to drones therefore likely reflects both the reduced sensory cues associated with aerial observation and the absence of a direct human approach. As such, drones operating at moderate altitudes have frequently been reported to cause less or no visible disturbance in a range of both diurnal and nocturnal species (as reported in e.g. Kays *et al.* 2019; Barr *et al.* 2020; Beranek *et al.* 2020; Schroeder *et al.* 2020; Rahman *et al.* 2021; Geldart *et al.* 2022; Colombelli-Négrel *et al.* 2023; Norris 2025). Drones as aerial stimuli may be perceived as distant or unfamiliar, eliciting less behavioural disruption (McEvoy *et al.* 2016; Schad and Fischer 2022). The lower sensitivity of generalist species may reflect a combination of ecological flexibility, habituation to a wider range of stimuli, through e.g. larger home-range sizes and occurrence in a wider range of habitat types, and risk–reward trade offs in which the energetic cost of vigilance outweighs the perceived threat (Čapkun-Huot *et al.* 2024). By contrast, a higher sensitivity to audible stimuli of gliding or more specialised species such as yellow-bellied gliders or koalas may be due to these species' reliance on acoustic communication for territorial defence and during the breeding season (Charlton *et al.* 2013; Whisson *et al.* 2021).

One explanatory factor for the contrasting behavioural responses between survey methods may also be the nature of the lighting used for species identification. Spotlighting typically involves a narrow, intense beam directly focused on an individual animal (Allison and Destefano 2006; Chick *et al.* 2020), which may startle the individual and can trigger vigilance due to its sudden brightness and apparent targeting (Ollivier *et al.* 2004; Dimovski *et al.* 2025). By contrast, our drone surveys employed diffuse, wide-angle illumination, which spread light more evenly over the habitat and avoided direct fixation on animals (Wagner *et al.* 2025). This difference in light intensity and focus may reduce the perceived threat, allowing animals to maintain non-vigilant behaviours during drone surveys.

For future wildlife monitoring, our findings suggest that drones may offer a less invasive alternative for observing nocturnal arboreal species in temperate eucalypt forests, with the added benefits of increased survey area and the ability to derive more accurate detections and population estimates (Corcoran *et al.* 2021; Ryan *et al.* 2025; Wagner *et al.* 2025; Kremer *et al.* 2026). In considering animal observation during wildlife surveys, minimising behavioural

disturbance is critical not only for ethical considerations but also for ensuring that survey data accurately reflect natural behaviour and habitat use (Marchowski 2021; Schad and Fischer 2022). Nevertheless, it remains important to evaluate potential variation among species and environmental contexts, as sensitivity to aerial stimuli may differ depending on survey method and equipment, as well as target species, sex, body size, habitat type or reproductive period (Mulero-Pázmány *et al.* 2017).

Limitations and future research

As is common in wildlife behavioural studies, the circumstances of the observation and observation time will affect observed behaviour and behavioural transitions of the individuals observed (Witmer 2005; Tablado and Jenni 2017). In the case of our drone observations, the purpose of the collected video footage was primarily for species identification (Wagner *et al.* 2025), and we can therefore not be sure if the observed individual may have noticed or responded to the drone flying overhead, before video footage was captured. Although our test for the influence of footage length showed no influence of time spent observing on the likelihood of exhibiting vigilant behaviour, we cannot rule out that some individuals may have already noticed the drone and reacted to it while the drone was surveying overhead but had not yet moved toward the individual. Given that some of the initial behaviours observed were classified as vigilant, it is likely that this occurred and this potential transition in behaviour could not be considered in our analysis. As we found species-specific and seasonal differences in the likelihood of expressing vigilant behaviour in response to drone observation, a more targeted approach could be employed in future research to further investigate drone disturbance impacts on nocturnal arboreal mammals. As environmental and habitat conditions such as canopy cover (Colombelli-Négrel *et al.* 2023), weather conditions and climate (Laurance 1990; Wagner *et al.* 2020; Tan *et al.* 2025), as well as season and breeding behaviour influence behaviour, occurence and detection of nocturnal arboreal fauna (Beranek *et al.* 2020), such a targeted approach should also further consider the effects of these variables on behavioural response to drone observation.

Behavioural analyses were conducted using descriptive statistics and contingency tests, which do not explicitly account for the hierarchical structure of the data, including nesting of observations within individuals, surveys, sites and seasons. Although mixed-effects models are well suited to such data, their application to this dataset was limited by sparse and unbalanced replication across grouping levels, particularly the low frequency of repeated observations of identifiable individuals. Therefore, behavioural results should be interpreted as indicative of broad patterns rather than definitive inferential outcomes. Future studies designed specifically to assess behavioural responses would benefit from structured replication that supports mixed-effects modelling, allowing random effects to be incorporated and improving inference regarding individual-, site- and survey-level variation in responses to drone surveys.

Spotlighting and drone-based observations differ inherently in how animals are detected and observed, which introduces unavoidable methodological bias. Comparisons between methods are influenced by intrinsic differences in illumination type, duration of observations, field of view and observer perspective (ground *v*. sky). These differences influence detection (Wagner *et al.* 2025), behavioural visibility (Beranek *et al.* 2020), and the potential for disturbance (Mulero-Pázmány *et al.* 2017; Schad and Fischer 2022). As a result, the two survey types can never be made fully comparable, and direct equivalence in behavioural response metrics cannot be assumed. Our analyses therefore focused on broad behavioural patterns of current operational survey methods, rather than attempting to standardise methods that differ in equipment, observer position, field of view and animal exposure. Approaches explicitly designed to control these variables would provide clearer insight into specific triggers of vigilance in nocturnal arboreal mammals during wildlife surveys to refine or improve currently employed methods.

Our findings indicate a generally low sensitivity of nocturnal arboreal fauna to drones in temperate eucalypt forests, although some increased vigilance was observed, especially during certain seasons and in particular species. Because stress responses in wild animals are only critical at a population level, as this affects survival or reproductive success (Gill *et al.* 1999), it will be important to further investigate if vigilance due to observation by either drone or from the ground by spotlight also invokes a physiological response in wild arboreal mammals. Although some research suggests that observation does not cause physical stress responses in some species (see e.g. Barr *et al.* 2020; Geldart *et al.* 2022; Colombelli-Négrel *et al.* 2023), other studies have recorded negative physiological effects (Ditmer *et al.* 2015; Weimerskirch *et al.* 2017). However, few behavioural studies have been conducted on the suite of species observed in our study and such studies are especially difficult outside captive environments (Stankowich and Blumstein 2005). Nevertheless, detailed species-specific knowledge on impacts of wildlife surveys on animal populations are critical in a time where monitoring efforts are increasing due to conservation concerns (Lahoz-Monfort and Magrath 2021) and technological advances (Buettel *et al.* 2025).

Conclusion

We demonstrate that drone-based wildlife surveys elicit low vigilance and disturbance responses in multiple nocturnal arboreal mammal species and associated forest fauna. The majority of observed animals maintained calm behaviours

during drone surveys, with only a small proportion exhibiting vigilance. No instances of flight behaviour in response to drone presence were recorded. Species-specific analyses indicate that generalist species were particularly tolerant, whereas gliding and more specialised species, including southern greater gliders and yellow-bellied gliders, showed higher – but still limited – vigilance. Seasonal variation further influenced behaviour, with higher vigilance observed during autumn, coinciding with breeding and post-breeding periods. The reduced responses to drones likely reflect a combination of factors, including lower sensory cues, absence of direct human contact and diffuse illumination, whereas spotlighting may provoke stronger reactions due to its focused, intense light. Our findings suggest that drones provide a minimally invasive method for monitoring nocturnal arboreal mammals, allowing for ethical and effective wildlife surveys when accounting for species-specific and seasonal sensitivities.

Research permit and ethics approval

This research was conducted with an access agreement for parks and reserves from Parks Victoria and a research permit and animal ethics permit for surveys in state forests issued by the Victorian Department of Energy, Environment and Climate Action (DEECA, permit number 2022-01-25). Spotlighting surveys for arboreal fauna were conducted with The University of Melbourne animal ethics approval (identification number 2021-22840-21795-2).

Supplementary material

Supplementary material can be accessed from the article page online.

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Data availability. Codes and datasets supporting the findings of this research are available on Github (see https://github.com/BennyWag/drone-behaviour). Animal observation locations are publicly available in the Victorian Biodiversity Atlas (see https://vba.biodiversity.vic.gov.au/vba/#/).

Conflicts of interest. The authors declare that they have no conflicts of interest.

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