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ARTICLE

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Thermal drone surveys to detect arboreal fauna: Improving population estimates and threatened species monitoring

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Abstract

Sound methods to determine species occurrence and abundance are crucial for successful wildlife management and conservation. When species communities cannot be readily detected using camera traps or acoustic monitoring, ground survey methods such as spotlighting on foot are commonly used. While able to provide precise detection and density estimates, these methods can be laborious and time consuming and are restricted to surveying small areas. Advances in drone technology now allow for the detection of heat signatures of endothermal wildlife using thermal cameras from the sky, which we contrast to traditional ground surveys. We found that drone and ground surveys achieve similar detection probabilities for nocturnal arboreal mammals of southeastern Australia. Drones achieved high detection rates for targeted arboreal wildlife occurrence and consistently recorded more species and individuals than ground-based surveys via spotlighting. Ground surveys often missed specialist species like the endangered southern greater glider (*Petauroides volans*) when populations had low densities. Drone-derived density estimates for surveyed areas of 100–200 ha were significantly lower than those extrapolated from 10-ha ground survey results. Thermal drone surveys present a promising tool for measuring and monitoring nocturnal arboreal wildlife populations due to their ability to cover larger areas with comparable detection rates to ground surveys. Drone surveys provide comprehensive information on species assemblage, density, and distribution across management compartment-scale survey areas, offering valuable insights into species occurrence and population status. Drones were particularly effective in areas with dense vegetation or that were otherwise inaccessible for ground-based surveys, enhancing the ability to estimate populations, quantify recovery following large-scale disturbances, and to discover previously undocumented populations. Drone-based wildlife survey methods have the potential to reduce uncertainty in compartment-scale population estimates for improved wildlife monitoring and conservation.

KEYWORDS
arboreal fauna, distance sampling, drone, population estimates, spotlighting, thermal imagery, threatened species, wildlife survey

INTRODUCTION

The selection of effective and efficient methods for surveying wildlife depends on the target species' behavior and physiology, as well as their habitat (Marta et al., 2019). For terrestrial fauna with diurnal life cycles occurring in open habitats, visual surveys, transect walks, or fixed-area observations can be readily applied (Buckland et al., 2000; Eberhardt, 1978). For more cryptic species that are either hard to detect visually, are locally rare, or have large home ranges, camera traps, acoustic monitoring, or live trapping are commonly used (Burton et al., 2015; De Bondi et al., 2010; Sugai et al., 2019). Where target species are not easily attracted to cameras or do not commonly produce audible vocalizations that can be recorded, active searches are required (Parker, 1979; Skalski, 1994).

These most commonly involve transect surveys reliant on active visual scanning of the environment for signs of the targeted species. For example, a common approach for arboreal fauna is the use of torchlights to detect eyeshine reflectance of nocturnal mammals (Allison & Destefano, 2006; Chick et al., 2020). This method's detection rate can be enhanced by the use of thermal cameras, which are able to identify heat signatures of endotherms for subsequent identification using torchlights and binoculars (Vinson et al., 2020).

Most survey methods allow monitoring the status and size of wildlife populations to inform management and conservation efforts (Witmer, 2005). A key factor in assessing the trajectory of threatened wildlife populations is the estimation of abundance and population density of target species within a given area or across their habitat range. Continuous monitoring with appropriate methods allows for the detection of trends in these metrics over time and can be used to inform decisions regarding their conservation status and when population management might be required (Williams et al., 2002). Species abundance and population density are most commonly derived using mark–recapture methods, distance sampling (Burt et al., 2014; Cripps et al., 2021; Laake, 1999), or occupancy modeling (MacKenzie et al., 2017). Such approaches can, however, be prone to sources of error or uncertainty, and extrapolations from survey results to local or larger scale population estimates may therefore be inaccurate (Otis et al., 1978; Williams et al., 2002). In surveys for nocturnal arboreal fauna or other cryptic wildlife, imperfect detection can be a major factor in increasing uncertainty in these estimates and requires multiple survey nights to increase accuracy (Kéry et al., 2009; MacKenzie et al., 2005; Royle et al., 2005). Even after multiple visits, not all individuals may be present in the survey area or active at the time of survey to be detected. The result may, therefore, be an underestimation of species occurrence, population size, and density (Kéry & Schmidt, 2008; Lindenmayer et al., 2001; Wintle et al., 2005). Sampling bias, as well as accessibility, further confounds population estimates, for example, when survey transects lead through more accessible but potentially less suitable or favorable habitat or if surveys are conducted where parts of the forest canopy are not visible due to dense mid- or understory vegetation (Bart et al., 2004; Tyre et al., 2003; Wintle et al., 2004).

For threatened and endangered wildlife with specific habitat requirements, sound population and density estimates are critically important for effective monitoring and conservation (Morrison, 2013). In cases where such species occupy habitat that is prone to disturbance or under active management (e.g., timber harvesting or planned burning), it may be crucial to be able to detect most or all individuals to protect their home ranges and apply appropriate habitat retention to ensure the survival of local populations (Kavanagh, 2000; Wagner, Baker, & Nitschke, 2021).

Methods that allow holistic surveys of areas relevant to species home ranges or local populations could therefore greatly improve population estimates and allow for better management, conservation, and protection from anthropogenic disturbances. To facilitate this, ground surveys could be expanded from single or multiple transects to a systematic grid covering a larger area to improve abundance and density estimates (see, e.g., Kavanagh, 1984). However, there are a range of operational, budgetary, and safety limitations associated with such survey programs (Delisle et al., 2023; Howell et al., 2021), limiting their application. Additionally, in dense and/or mature forest environments, systematic ground surveys would still include areas of dense vegetation affecting visibility of the canopy and therefore reducing detectability. Further, topographically inaccessible parts of the survey area are unlikely to be surveyed using ground-based surveys due to concerns for surveyor safety.

Technological advancements and increasing accessibility and affordability of remote sensing tools and thermal imaging technology have created promising avenues for improving wildlife detection and monitoring. Unoccupied aerial vehicles (UAVs or drones) equipped with infrared detectors that allow capturing real-time and high-resolution thermal imagery have found application in a range of habitats to detect a wide range of species including koalas (*Phascolarctos cinereus*), sea turtles, and nocturnal birds (Sellés-Ríos et al., 2022; Shewring & Vafidis, 2021; Witt et al., 2020). Advantages of using drone surveys are an increased survey area, the ability to survey otherwise inaccessible areas, and potentially decreased influence of vegetation density on visibility and detectability. Using drones as opposed to airplanes and helicopters also reduces costs, safety risks for surveyors, and, potentially, disturbances to wildlife (Gonzalez et al., 2016; Howell et al., 2021; Mulero-Pazmany et al., 2017). Because aerial surveys can cover larger areas while scanning for thermal signatures without obstruction from topography and vegetation (Beaver et al., 2020; Witt et al., 2020), they may be well suited to conduct systematic population assessments and improve respective abundance and density estimates by increasing detectability.

Applications of thermal drones for wildlife surveying are still sparse, even though evidence exists that such surveys can outcompete transect-based ground surveys (Baldwin et al., 2023; McCarthy et al., 2022; Povlsen et al., 2022; Zhang et al., 2023). In Australia, drones have been tested in the detection of the regionally endangered koala. These studies found increased detection rates and cost-effectiveness using drones compared to ground-based surveys (Howell et al., 2021; Witt et al., 2020). The method is often used by specialized survey contractors to detect koalas in commercial timber plantations and protect them from subsequent harvesting operations (Beranek et al., 2020; Hamilton et al., 2020). Application of the approach on other mature forest-dependent arboreal fauna, commonly surveyed using transect-based spotlighting techniques, is sparse. Thermal drone surveys have however recently been reported to be effective for Bennett's tree kangaroos (*Dendrolagus bennettianus*) during diurnal surveys in the tropical forests of northeastern Australia (Norris & Larson, 2025).

The evidence collected for koalas suggests that the method is well suited for the detection of species with distinct habitat requirements and small home ranges or that exhibit little movement (Beranek et al., 2020; Howell et al., 2021). As such, thermal drone surveys could be a promising survey technique for species such as the folivorous and endangered southern greater glider (*Petauroides volans*). The species has distinct habitat requirements for large tree hollows, *Eucalyptus* trees with foliage rich in foliar nitrogen, and cool, wet climates (McLean et al., 2015; Wagner et al., 2020; Youngentob et al., 2011). In recent decades, the species has been threatened by habitat loss through wildfire and timber harvesting (McLean et al., 2018; Wagner et al., 2024), as well as climate change (Smith & Smith, 2020; Wagner et al., 2020). Most recently, the 2019/20 Black Summer Bushfires burned large areas of the species' range in eastern Australia, causing declines in habitat availability and quality and local population loss (Driscoll et al., 2024; Green et al., 2024; Smith & Smith, 2022; Ward et al., 2020).

In the state of Victoria, Australia, concerns over population declines resulted in targeted surveys for southern greater gliders as part of the Forest Protection Survey Program (Chick et al., 2020; Lumsden et al., 2020) to detect and protect populations from timber harvesting and other potential threats. Commercial timber harvesting from state forests ceased in Victoria in 2024. Regenerating stands from stand replacement timber harvesting or stand replacing fire will now slowly mature into future habitat, while other forest habitat is still recovering from the most recent megafires that affected the east of the state (DAWE, 2021; Driscoll et al., 2024). Given their wide distribution in Victoria (Wagner et al., 2020), drone surveys may greatly enhance the capability to monitor the recovery and population trajectories of southern greater gliders and associated arboreal mammals in southeastern Australia. Detection rates and efficacy of aerial survey methods for arboreal fauna in native temperate forests of Australia have, however, not been quantified.

In this study, we hypothesized that thermal drone surveys can produce more comprehensive survey results and more precise abundance estimates than ground surveys for mature-forest dependent fauna such as the southern greater glider. We sought to quantify the efficacy of novel remote sensing methods of surveying for threatened and endangered nocturnal arboreal fauna, including the endangered southern greater glider, using drones and thermal imagery. The primary aims of our research were to:

1. Compare survey results from aerial surveys using drones and thermal imagery with ground surveys (spotlighting on foot) for nocturnal arboreal fauna in the same forest habitat.
2. Derive likelihood of species detection from drone surveys and contrast with ground survey detectability.
3. Compare abundance and density estimates from both survey methods.

METHODS

Study area and target species

All wildlife surveys were conducted in the tall eucalypt forests of the Central Highlands east of Melbourne and in the Wombat State in western Victoria, Australia. These forests are composed of a range of temperate *Eucalyptus* species, including the iconic mountain ash (*E. regnans*)—the world's tallest angiosperm (Wood et al., 2010), as well as mixed species forests of species such as messmate (*E. obliqua*), narrow-leaved peppermint (*E. radiata*), and mountain gray gum (*E. cypellocarpa*).

A range of arboreal mammals occurs in the mature forests of this region, including the critically endangered Leadbeater's possum (*Gymnobelideus leadbeateri*) and the endangered southern greater glider. Other arboreal species found in the region are the common- and mountain brushtail possum (*Trichosurus vulpecula* and *T. cunninghami*), the common ringtail possum (*Pseudocheirus peregrinus*), the feathertail-, Krefft's-, and yellow-bellied gliders (*Acrobates pygmaeus, Petaurus notatus*, and *P. australis*), and the koala. We selected 30 forest management coupes (henceforth "compartments") that had either not been subject to timber harvesting or wildfires in the 60 years preceding the survey ($n = 18$) or were regenerating from variable intensity timber harvesting operations 10–30 years prior to the survey ($n = 12$). Compartment sizes ranged between 30 and 200 hectares (mean compartment area = 120 ha). Wildlife surveys were conducted between September 2023 and March 2024.

Survey design

We used DJI Matrice 300 and M30T drones (DJI, Shenzhen, China) equipped with 640 × 512 pixel radiometric thermal cameras (DJI Zenmuse H20T on Matrice 300 series drones, built-in thermal camera on M30T) for aerial surveys for arboreal fauna. These drones' sensors include a zoom camera (23× optical, 200× digital zoom), a laser range finder, and were paired with a strong floodlight. Surveys commenced 30–60 minutes after dusk and covered the entire compartment area, searching for heat signatures. Drones were operated manually by two pilots taking turns but followed a pre-programed survey grid of virtual transects at a fixed spacing for orientation. Transects were designed to follow a boustrophedon ("lawnmower") type survey pattern that maintained an overlapping field of view between transects placed 50 m apart (Appendix S1: Figure S1). Drones were operated at 20–50 m altitude above the tree canopy (maximum 120 m above ground in accordance with Australian Civil Aviation regulations, CASA, 2019). When a heat signature was detected, the floodlight mounted on the drone, in combination with its zoom camera, was used to observe the animal and to capture video footage. If unobstructed footage could not be taken from the angle at which the heat signature was first observed, the drone was moved horizontally or flown closer to the detection to acquire footage.

Each observation's location was recorded using the drone's GPS position and rangefinder to create a GPS waypoint reflective of the position of the observation. Recorded footage and location data were logged using a matching naming convention to later identify observed arboreal fauna using footage collected and spatially map observations for abundance and density calculations within the surveyed area. Species were identified based on collected video footage after surveys were completed. This resulted in a dataset of species observations (with date and time of observation), alongside spatial data of the location of these observations (waypoints) and the flight paths of the drone (line vectors). Subsequent second drone surveys were carried out at a later date (maximum of five days after the first survey) on a subset of half the compartments surveyed ($n = 15$) to derive the probability of occupancy of commonly observed species using N-mixture models (see below).

Spotlighting ground surveys were carried out on a set of three parallel 500-m transects placed 50 m apart within the area surveyed by drone (Appendix S1: Figure S1). They were carried out during a single night with two observers using double observer distance sampling methods (see Appendix S1: Section S3). Transects were laid out through the forest and placed within accessible areas of the compartment. Transects commenced at least 50 m from the nearest forest track. The ground survey grid was designed to allow comparisons of survey results and extrapolated population densities from single spotlighting transects—commonly used in ground surveys for nocturnal arboreal fauna (i.e., the first transect surveyed) with a larger area surveyed (i.e., three subsequent ground transects and the entire compartment via drone survey). Transects were spaced to ensure high detection probabilities from a single survey night. Cripps et al. (2021) reported that the probability of detection for southern greater gliders decreases with distance from the ground survey transect; 87% of all animals were detected within 25 m of the transect with two observers during a single survey. At 50 m, the likelihood decreases to 73% and at 75 m to 54%.

Multiple survey transects with a 50-m spacing were expected to increase the detection probability of potentially missed individuals on the preceding transects (Appendix S1: Figure S2) and emulate a systematic grid survey. To derive the effective survey area of ground surveys for population density estimates, we considered the median distance of all visual animal observations from the survey transect (~30 m), which led to an effective survey area of ~4 ha from a single transect and

~10 ha when considering all three parallel transects. A detailed description of the ground survey transect setup and data collection can be found in Appendix S1: Section-S3. Operational restrictions did not allow for drone and ground surveys to be carried out during the same night. Consequently, ground surveys were carried out after drone surveys were completed, within the same month to control for seasonality.

Deriving detectability and population density estimates

To derive population densities for comparisons between drone and ground surveys, we considered only species with 30 or more individual detections during drone and ground surveys (i.e., at least one detection per total number of survey sites). Focus species selection was driven by the ground survey results, which recorded fewer observations. Based on these criteria, the common ringtail possum and southern greater glider were selected for estimating population densities and subsequent comparisons between drone and ground survey results. A detailed description of ground survey data preparation and analyses can be found in Appendix S1: Section S3.

Occupancy, detectability, and population density from drone surveys

Occupancy and detectability for species commonly observed during the repeated thermal drone surveys ($n = 15$) were derived using N-mixture modeling according to Royle (2004) on abundance data and using occupancy modeling according to MacKenzie et al. (2002) on presence or absence data from the first and second survey night. To derive detectability, we first modeled detection as constant without additional covariates, assuming that detection probability is the same for all observations. We then tested whether average site vegetation density (based on ground assessments during survey transect setup) influenced detectability by including it as a covariate in the model. In both cases, we used a Poisson distribution to accommodate variability in counts between sites but assumed constant mean abundance across the 15 sites surveyed twice. As not all target species were detected in this subset of sites, we derived detectability and occupancy for brushtail possums (combining observations of common- and mountain brushtail possums), common ringtail possums, feathertail gliders, Krefft's gliders, and southern greater gliders.

To calculate population densities (animals per hectare) for common ringtail possums and southern greater gliders, we first used the derived detectability score (p) to correct the raw number of observations for potentially missed individuals. We then divided this abundance estimate for the area surveyed by the survey area in hectares (Equation 1).

$$\text{Animals per hectare} = \frac{\left(\frac{\text{Number of observations}}{\text{Detectability score } (p)}\right)}{\text{Area surveyed (ha)}}. \quad (1)$$

To compare drone with ground survey results, we extracted drone observations of these two species made within the footprint of the ground survey transects (first transect only and all three transects) and calculated abundance and density using the formula above for the respective ground survey area (4 or 10 ha).

Comparing survey results

To compare findings from drone and ground surveys, we tested for significant differences in the number of observations and density estimates within the survey footprint of 4 ha (one transect) and 10 ha (three transects) based on the ground survey transects. We then compared the density estimates derived from the ground survey with estimates for the entire compartment derived from the drone observations. This allowed for an assessment of whether extrapolations from smaller survey areas, common for ground surveys, can be scaled to larger areas accessible only through aerial surveys. Given the small sample size and surveys with no observations for both the common ringtail possums and southern greater gliders, we used Wilcoxon Signed-Rank tests to account for the non-parametric nature of the data when comparing paired observations (i.e., estimates from the same area using different survey methods).

We tested whether species detection was influenced by the placement of ground survey transects and the estimated population density of the compartment area based on drone observations using binomial generalized linear models (GLMs). We assumed that low population densities, common in medium- and low-quality habitat (Wagner, Baker, Moore, & Nitschke, 2021; Youngentob et al., 2015), would lead to lower probability of detecting the species from the spatially restrained ground surveys and would be dependent on transect placement. We calculated the nearest neighbor index (NNI, Clark & Evans, 1954) for observations recorded via thermal drone to test whether detection from the ground was more likely in higher density populations. First, we calculated the distance between each observation's coordinates and its nearest neighbor per survey. The NNI (Equation 2) is calculated as the mean observed nearest neighbor distance $(\overline{d}_{obs})$, divided by the expected mean distance based on the survey area (a) and number of observations (n):

$$\mathrm{NNI} = \frac{\overline{d}_{obs}}{0.5\sqrt{\frac{a}{n}}}. \quad (2)$$

The index scales between 0 and 2.15, where values between 0 and 1 indicate clustered populations and values between 1 and 2.15 describe dispersed conditions, tending toward regularity (Clark & Evans, 1954). Lower NNI values are indicative of higher population densities as average distances between observations should be smaller. We tested this assumption using a generalized linear model of site NNI predicting estimated population density from drone surveys across the compartment. As density data were right-skewed, we used a Gamma distribution with log-link. We then tested whether the target species were predominantly missed during ground surveys in compartments where the distribution of observations across the survey area resulted in high NNI values.

Survey area, length, and effort

A detailed description of the considerations and methods to determine effects of survey area, length, and resulting effort can be found in Appendix S1: Section S3. Most importantly, we assessed whether longer surveys or surveys over a larger area led to significantly more detections of all species combined, common ringtail possums, or southern greater gliders.

RESULTS

Observed species and number of observations

All nine arboreal mammal species known to be present in the study area were detected during drone surveys. In total, 1006 observations were recorded across the 30 forested compartments (Table 1). While species commonly surveyed using spotlighting were recorded most frequently, we also recorded species more commonly detected using remote cameras (e.g., Leadbeater's Possums) or vocalization (e.g., yellow-bellied gliders). Observations of terrestrial mammals, such as bare-nosed wombats (*Vombatus ursinus*) and introduced species such as sambar deer (*Rusa unicolor*), as well as a range of bird species, including forest owls, were also recorded. Only 2.5% (34 observations) could not be identified via video footage (Appendix S1: Table S1). In most cases, the operator could not achieve a clear view of the animal, with branches or other vegetation covering most of the individual or the individual moved out of view. Spotlighting surveys visually detected all targeted arboreal mammal species, except Leadbeater's possums and koalas. A total of 194 individual visual observations were made (Table 1). Some vocalizing species, such as koalas, yellow-bellied gliders, and forest owls, were typically recorded as "heard", but not included in further analyses (Appendix S1: Table S1).

TABLE 1 Number of individual visual observations of arboreal mammal species recorded from thermal drone surveys across the compartment and spotlighting surveys within the total ground survey footprint (10 ha).

Arboreal mammal species	No. observations by drone	No. observations by spotlighting
Common brushtail possum (*Trichosurus vulpecula*)	56	6
Common ringtail possum (*Pseudocheirus peregrinus*)	608	81
Feathertail glider (*Acrobates pygmaeus*)	44	4
Koala (*Phascolarctos cinereus*)	26	0
Leadbeater's Possum (*Gymnobelideus leadbeateri*)	3	0
Mountain brushtail possum (*Trichosurus cunninghami*)	20	10
Southern greater glider (*Petauroides volans*)	155	91
Krefft's glider (*Petaurus notatus*)	86	1
Yellow-bellied glider (*Petaurus australis*)	8	1

During drone surveys, the common ringtail possum and southern greater glider were recorded in 24 and 26 compartments, respectively. In those compartments, observations of common ringtail possums ranged from 1 to 146 individuals across the surveyed areas, while 1–25 southern greater gliders were detected. Spotlighting detected common ringtail possums in 15 compartments, with 2–19 observations. Southern greater gliders were found in 17 compartments, with the number of observations ranging between 1 and 21 individuals. On three occasions, drone surveys did not detect common ringtail possums, where spotlighting later recorded them. Spotlighting did not record them during 12 surveys, where drone surveys had previously recorded the species.

Drone surveys did not detect southern greater gliders in one compartment where they were detected via spotlighting, while spotlighting surveys did not detect the species in 10 compartments where drone surveys detected them (Appendix S1: Tables S2 and S3).

Species detectability and influence of vegetation density

For species with sufficient observations in compartments that were surveyed twice, we found that drone surveys had a high probability to determine species occurrence (Table 2) after two surveys over the same area. Detection probability for species abundance was highest for Krefft's gliders and lowest for feathertail gliders. Average site vegetation density had a significant effect on drone detectability of Krefft's and feathertail gliders (both $p < 0.001$) but not on brushtail or common ringtail possums and southern greater gliders (all $p > 0.6$).

Spotlighting surveys only produced sufficient individual detections to determine the probability of species occurrence and abundance of common ringtail possums and southern greater gliders (Table 1). We found higher probabilities of recording occurrence and abundance for southern greater gliders than common ringtail possums. Detectability was comparable between drone surveys and spotlighting surveys when three transects were considered. Detection probability for both species was higher when surveying a single (the first) transect, as compared to all three transects (Table 2). Average single observer detection probabilities were 0.7 (±0.1) and 0.51 (±0.09) for southern greater gliders on single- and three-transect surveys, respectively, and 0.3 (±0.16) and 0.24 (±0.08) for common ringtail possums.

A range of vegetation densities were estimated by ground surveyors across the transects in the 30 compartments surveyed. While most compartments had low-to-medium mid- and understory vegetation density ($n = 23$), seven had on average high vegetation density (Appendix S1: Figure S3). Mean vegetation density (on a scale from 1 to 3, 3 being the highest) was 1.7 (±0.3). When we compared MRDS models with an added vegetation density covariate in the mark–recapture component to distance-only models, we found that models that included vegetation density improved model performance. Delta Akaike information criteron values of models with vegetation density were 14.67 for southern greater gliders and 2.88 for common ringtail possums. Likelihood ratio tests found significant improvements in model performance when adding vegetation density as a covariate (all $p < 0.0001$), indicating a significant influence of both distance from transect and vegetation density on detectability during ground surveys.

Comparing survey results

Using the footprint of a single (the first) ground transect (4-ha survey area) and all three transects (10-ha survey area), we compared the number of observations and respective density estimates. Estimated densities for common ringtail possums from spotlighting surveys in compartments where the species was detected ranged from 0.4 to 4 animals per hectare from the first transect and 0.3–4.9 from three transects. Estimates for the same survey footprint from drone surveys were 0.35–2.6 and 0.14–1.6, respectively, and 0.01–2.22 for the compartment area. For southern greater gliders, spotlighting density estimates ranged from 0.22 to 1.4 for a 4-ha survey area and 0.13–2 animals per hectare for 10 ha. Density estimates for southern greater gliders from drone surveys were 0.25–1.8 for the 4-ha ground survey footprint, 0.01–1.4 for 10 ha, and 0.01–0.92 for the entire compartment area.

We did not find significant differences between the paired number of ground and drone observations for both species from one ($p = 0.59$ for common ringtail possums, $p = 1$ for southern greater gliders) or three transects

TABLE 2 Species detection (occurrence) and abundance (number of individual observations) probability (p) for different survey types with standard errors in brackets.

Survey type	Drone (compartment)		Spotlighting—single transect (4 ha)		Spotlighting—three transects (10 ha)	
Spp./metric	p detection	p abundance	p detection	p abundance	p detection	p abundance
Brushtail possums[a]	1	0.57 (±0.13)	...	...	...	...
Common ringtail possum	1	0.59 (±0.03)	0.7 (±0.13)	0.51 (±0.23)	0.8 (±0.09)	0.43 (±0.1)
Feathertail glider	1	0.31 (±0.08)	...	...	...	...
Krefft's glider	1	0.84 (±0.04)	...	...	...	...
Southern greater glider	1	0.79 (±0.05)	0.88 (±0.07)	0.9 (±0.06)	0.86 (±0.07)	0.77 (±0.08)

Note: Probability of abundance for spotlighting surveys is given as the average combined probability from two observers. Estimates for single-transect spotlighting surveys were derived from observations made on the first of three transects surveyed.

[a]Observations of common- and mountain brushtail possums were combined to determine detectability for these species.

($p = 0.55$ and $p = 0.7$, respectively). Similarly, density estimates from the two survey methods in the same footprints did not differ significantly (Figure 1). Individual observations (total number) made by the drone across the entire compartment were significantly higher than those observed by spotlighting within the 10-ha survey footprint (p for both species <0.05). While population density estimates for common ringtail possums across the compartment did not differ significantly from those based on spotlighting observations for the 10-ha survey footprint, density estimates for southern greater gliders were significantly lower when based on observations by drone for the entire compartment, as compared to ground observations from the 10-ha footprint ($p = 0.001$).

Species absences recorded through spotlighting surveys predominantly occurred in compartments with low population density estimates according to drone surveys. For example, the 10 compartments where southern greater gliders were missed during spotlighting surveys but were detected by thermal drone had population density estimates ranging from 0.03 to 0.1 animals per hectare. For both common ringtail possums and southern greater gliders, estimated compartment-level population density from drone observations could explain the probability of species detection by ground survey (both $p < 0.05$). At estimated densities below 0.5 animals per hectare for common ringtail possums and below 0.125 animals for

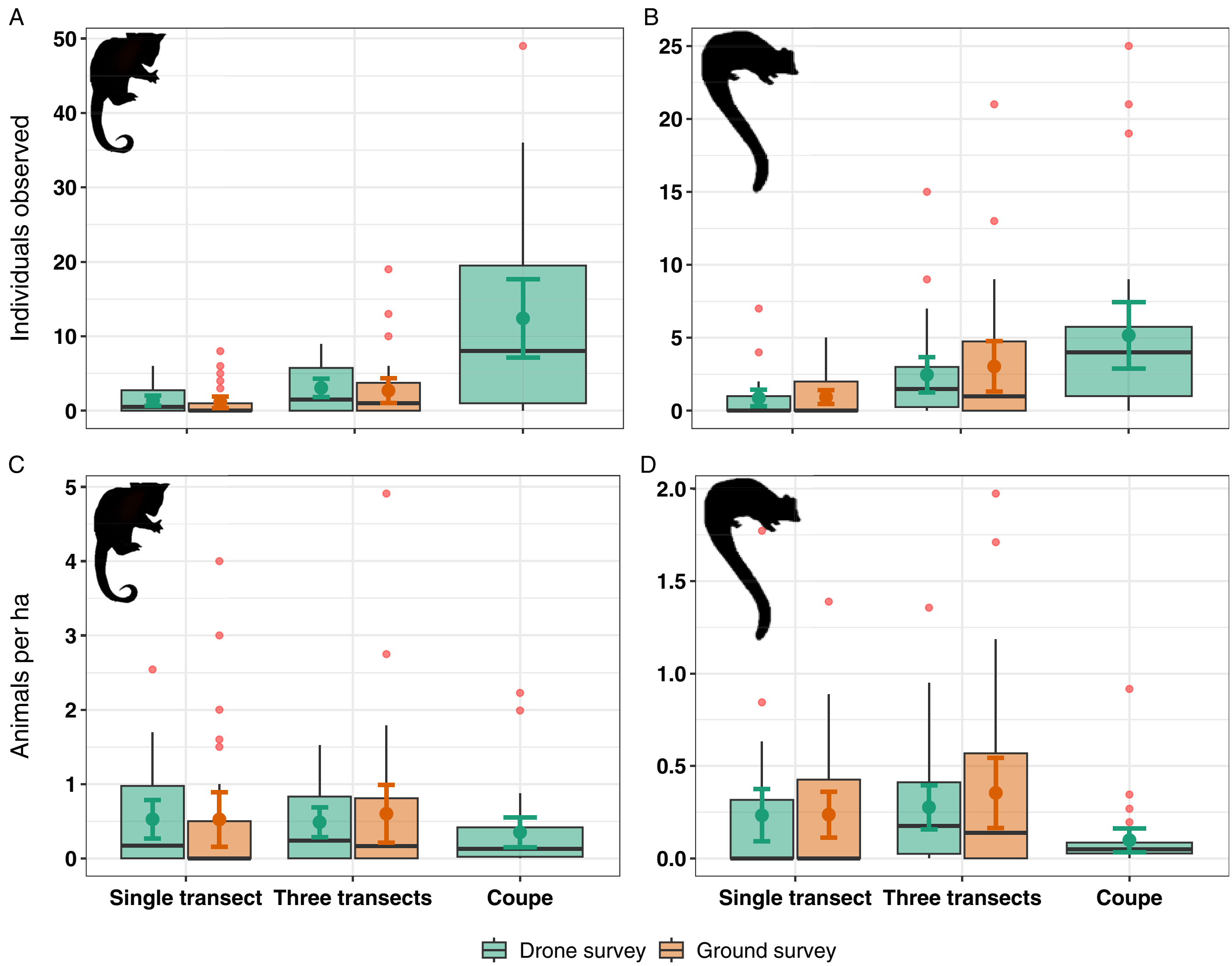

FIGURE 1 Number of individual observations of common ringtail possums (A) and southern greater gliders (B) and respective density estimates (C, common ringtail possums; D, southern greater gliders) from ground and drone observations within the footprint of a single- (the first, 4 ha) or three-transect (10 ha) ground survey and across the entire compartment (drone only). Note that one compartment with a total number of 146 common ringtail possum observations by drone was removed from the figure as an outlier. Outliers are illustrated as red points, boxplots show the median, upper, and lower quantiles as well as minimum and maximum values. The error bar overlay illustrates the mean (dot) and 95% CIs (bars). Animal silhouettes were adapted from Lindenmayer (1996).

southern greater gliders, the likelihood of detection by ground survey was ~66% (Figure 2).

Transect placement for ground surveys, as well as the spatial distribution of individual animals across the compartment area affected density estimates from both ground and drone surveys. This was especially pronounced for the southern greater glider. When populations were small and highly dispersed, ground surveys often failed to detect the target species, resulting in an estimate of species absence. The ability of the drone to survey a larger area increased the likelihood of detection of the species in areas with a low population density. In cases where drone surveys did not detect significantly more individuals in the larger area surveyed but detected similar numbers of observations made within the ground survey footprint, population densities varied the most. Only in cases where individuals were dispersed across both the ground survey footprint and the compartment area were ground- and drone-survey density estimates comparable when results were scaled to the compartment area (Figure 3). The nearest neighbor index (NNI) analysis supported this relationship: NNI significantly increased with decreasing population density estimates from drone observations ($p < 0.001$, Appendix S1: Figure S4). In compartments where ground surveys did not detect southern greater gliders, NNI values ranged from 1.4 to 2.15, indicating highly dispersed populations and low overall population densities.

Survey area, length, and effort

A detailed description of the analyses of drone and ground survey length and effort and respective implications on observations can be found in Appendix S1: Section S3. During drone surveys, survey area and number of total observations recorded both significantly affected survey length of thermal drone surveys (both $p < 0.001$). Longer surveys had significantly more total observations ($p = 0.001$), as did surveys covering larger areas ($p = 0.02$, Figure 4A,B). In sites where common ringtail possums were detected, longer surveys or surveys over larger areas recorded significantly more observations of the species ($p = 0.007$ and $p < 0.01$, respectively, Figure 4C,D), while for southern greater gliders, the total number of observations was not affected by survey length ($p = 0.16$, Figure 4E) or area ($p = 0.19$, Figure 4F).

DISCUSSION

We present evidence that drones equipped with thermal cameras are a promising remote sensing tool for compartment-scale (100–200 ha) wildlife surveys for nocturnal arboreal fauna. Drones produced good detection probabilities for the targeted species with high success rates at recording species occurrence (presence/absence, Table 2). Detection probabilities for the abundance of common

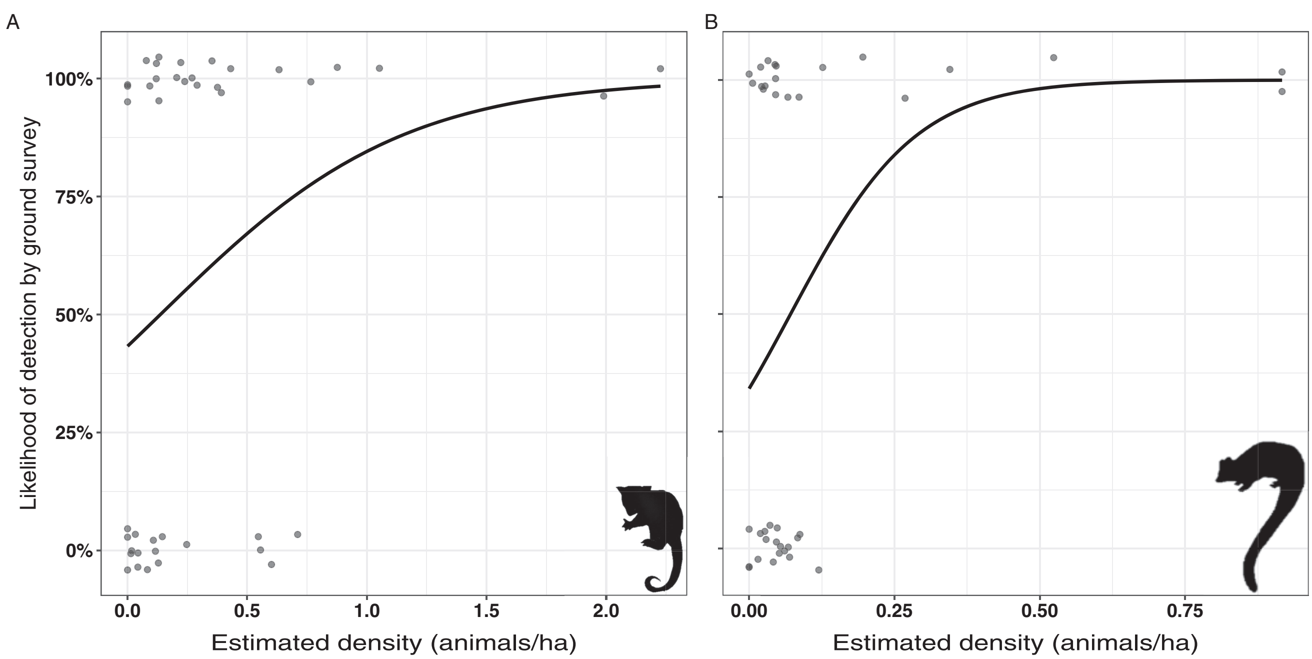

FIGURE 2 Species likelihood of detection curves based on estimated animal density across the compartment from drone surveys for common ringtail possums (A) and southern greater gliders (B). Data points were slightly jittered to avoid overlapping. Animal silhouettes were adapted from Lindenmayer (1996).

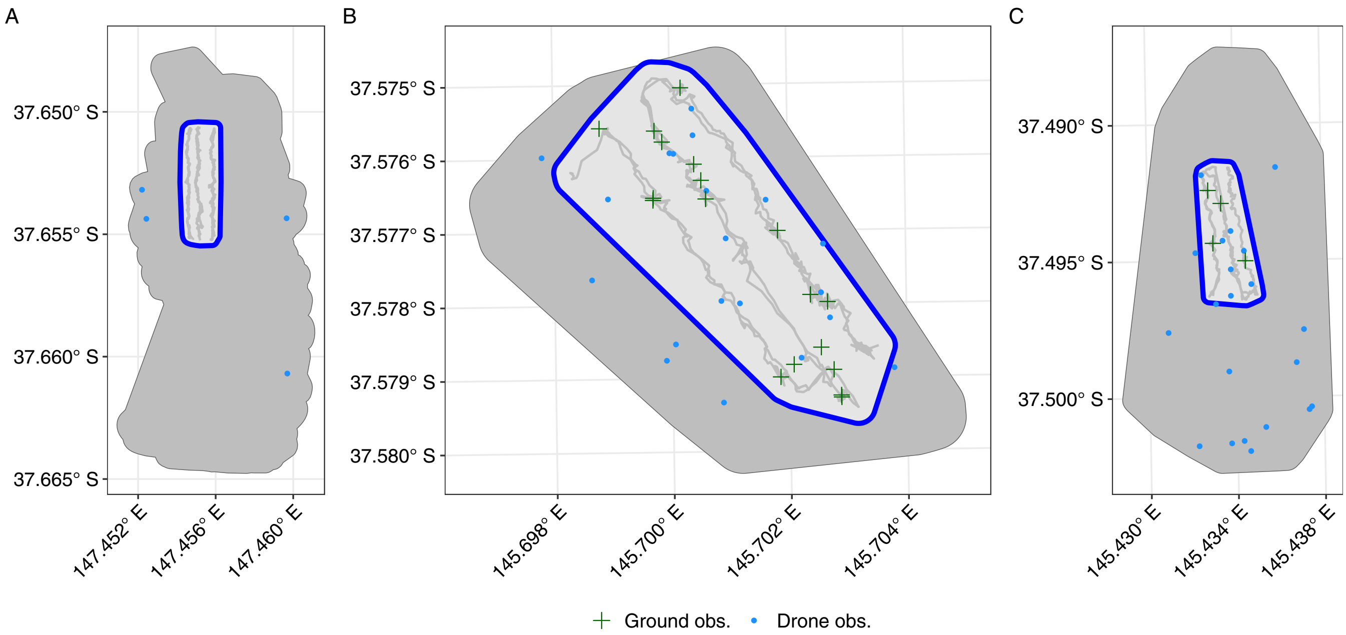

FIGURE 3 Three examples of the interplay of transect placement, spatial distribution of individuals, and population density estimates for southern greater gliders from ground and drone surveys. Compartment (A) recorded no observations from spotlighting transects (gray lines) within the 10-ha ground survey area (blue boundary), but four animals were recorded outside the ground survey footprint by thermal drone survey. The area surveyed was 131 ha (dark gray), leading to a population density estimate of 0.05 animals/ha. The nearest neighbor index (NNI) was 2.1, indicating a highly dispersed, small population. In compartment (B), the same number of southern greater gliders (21) was detected by ground surveys within the 10-ha survey area and in the 30-ha compartment area by drone. Population density from ground surveys was estimated at 1.9 animals/hectare, while drone survey results led to an estimate of ~0.9 animals/ha. The NNI for this compartment was 0.75, indicating a clustered, dense population. Compartment C represents conditions where both ground survey and drone survey density estimates aligned. Five observations within the ground survey area resulted in estimates of 0.4 animals/ha, while the estimate for the entire compartment from drone observations was 0.3 animals/ha from a total of 25 observations over 118 ha. The NNI was 1.2, indicating a moderately dispersed population. Clustering of individuals in the southern part of the survey area can be observed.

ringtail possums and southern greater gliders based on drone surveys were comparable to those achieved from spotlighting surveys on the ground as were numbers of observations and density estimates within the same survey footprint.

Due to the ability to survey larger areas, drones performed better at detecting small and dispersed populations of the endangered southern greater glider, a species with distinct habitat requirements and small home ranges (Kavanagh & Wheeler, 2004; Wagner, Baker, & Nitschke, 2021; Youngentob et al., 2011), which were frequently missed during ground surveys on fixed transects surveying a smaller area. Drones consistently recorded more observations, including of species that are rarely observed, either visually or at all, during spotlighting surveys (Tables 1 and S1). The combination of an aerial view, thermal imagery, and a larger survey area made possible by using a drone allowed for detection of species whose detection is highly dependent on their ecology and behavior. During spotlighting surveys, species such as Krefft's- or yellow-bellied gliders are more commonly recorded as "heard" through their calls, and while these observations allow to determine species occurrence, such records cannot readily be used for population density estimates through distance sampling (Whisson et al., 2021). Small species such as Leadbeater's possums or feathertail gliders are highly mobile and therefore hard to detect via eyeshine reflection and are more commonly detected via camera trapping (Chick et al., 2020; Lumsden et al., 2020; Nelson et al., 2017).

The ability of drone-based aerial wildlife surveys to sample larger areas compared to ground transects has implications for determining the occurrence of rare, threatened, or endangered species in areas of the landscape with pockets of suitable habitat intermixed within areas of lower habitat quality (Howell et al., 2021; Olsen et al., 2023; Zhang et al., 2020). An underestimation of southern greater glider occurrence and density in these areas has major implications for population estimates and the conservation of such species (Lindenmayer et al., 2001; McCarthy et al., 2022). Of further importance is that spotlighting surveys produced higher population density estimates than drone surveys when extrapolated to the compartment scale, indicating that results from

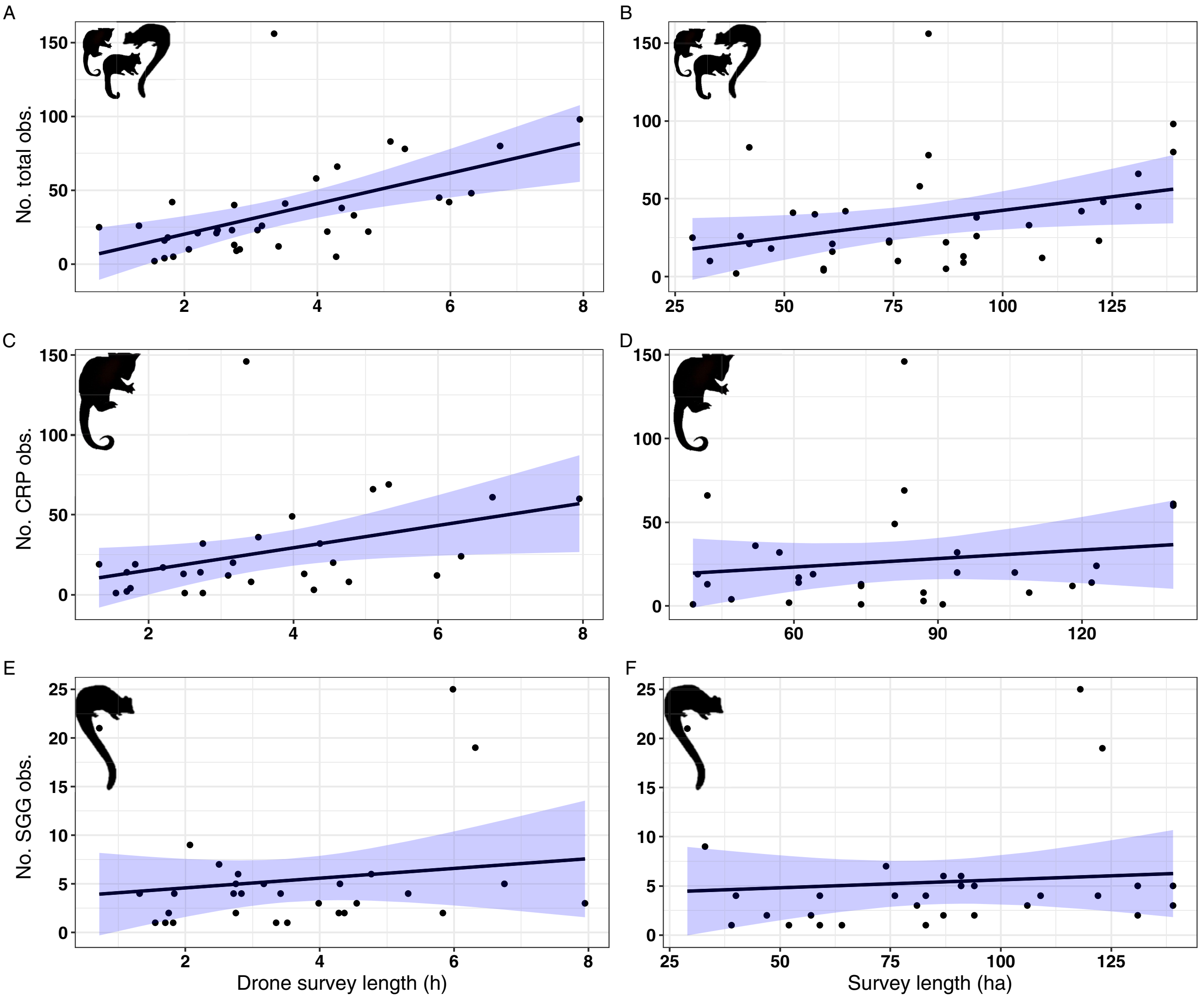

FIGURE 4 Relationship of number of total observations (A and B, individuals of all species observed), common ringtail possums (CRP, C and D), and southern greater gliders (SGG, E and F) by drone with survey length and survey area. Similar relationships were observed from ground survey results for survey length (see Appendix S1: Figure S6). Animal silhouettes were adapted from Lindenmayer (1996).

ground surveys may not readily scale up to areas up to 200 ha. This is likely where the species has a clustered distribution of habitat within an area that is targeted by a transect survey and may lead to overestimates of population sizes at broader spatial scales (Figure 3).

For specialist species such as southern greater gliders, detections depend on the quality and dispersion of sampled habitat and the placement of ground survey transects. Our results show that ground survey transect placement needs to be carefully planned and paired with habitat quality assessments that go beyond the spotlighting survey footprint. A drone-based survey approach based on the methods we present is not confounded by the habitat quality and survey location interaction. For the southern greater glider, our findings that a longer survey or surveying larger areas did not result in significantly more observations (Figure 4) further support these implications. For specialist species with distinct habitat requirements, such as the availability of large hollow-bearing trees and occurrence of preferred foraging tree species, it is inherently more important to survey within suitable habitat, rather than surveying across a large area (Gibbons & Lindenmayer, 2002; Wagner, Baker, Moore, & Nitschke, 2021).

Management and monitoring implications

Drone-based surveys can provide a safe and effective approach for rapidly assessing the impacts of disturbance such as bushfires, planned burning, or timber harvesting on arboreal fauna. Following the 2019/20 megafires in eastern Australia, ~54% of sites occupied by southern greater gliders (based on location records from 2000) were within the fire footprint and ~37% of this habitat was burnt at high severity (Ashman et al., 2021). The impacts of these fires on southern greater glider populations and its habitat were reported declines in site occupancy and habitat suitability as a function of fire severity (Driscoll et al., 2024; Green et al., 2024; Knipler et al., 2023; Smith & Smith, 2022; Wagner et al., 2024). These results were based on ground survey transects that were limited in survey effort (i.e., number of sites and area sampled) and potentially confounded by the impact of transect placement and vegetation density (Figures 2 and 3).

In areas where a mosaic of fire severities has occurred in habitat for arboreal fauna, population densities are likely to decline (Green et al., 2024) and populations will become spatially clustered into areas where habitat remains (i.e., refugia) within a post-fire matrix of unsuitable habitat (Wagner, Baker, & Nitschke, 2021). In these circumstances, and based on our results presented here, ground-based surveys may miss animals and underestimate post-disturbance persistence, whereas drone-based surveys have a higher likelihood of detection, especially when individuals occur in areas that are difficult or impossible to access due to roading, topography, or safety constraints (Beranek et al., 2020).

The ability to measure and monitor areas of refugia habitat within post-disturbance landscapes is critical for understanding how populations recover over time and in space, as well as for immediate post-disturbance surveys to monitor their initial impacts. Green et al. (2024) found that the population density of southern greater gliders was lower in refugia within the 2019–2020 fire extent compared to forests outside the fire extent. This has important implications for the population viability of isolated populations within the 2019–2020 fire extent having lower genetic diversity and effective population sizes (Knipler et al., 2023). The ability to comprehensively map the occurrence of individuals within fire extents will enable more accurate estimates of local population sizes immediately after disturbance and monitor their recovery rates over time.

Until the cessation of commercial timber harvesting on public land in Victoria in 2024, pre-harvest surveys were regularly conducted in management compartments likely to provide habitat for threatened arboreal species. Uncertainty surrounding the robustness of ground survey methods for arboreal marsupials led to a Supreme Court of Victoria court case (East Gippsland Inc v VicForests (Victorian Supreme Court VSC 668, 2022) where the Court concluded that commonly used transect survey methods failed to adequately detect individual southern greater gliders occurring within managed forests scheduled for timber harvesting. The court ordered that to ensure protection of the endangered southern greater glider, surveys must be able to detect any individual that may be present within the managed compartment (East Gippsland Inc v VicForests (Victorian Supreme Court VSC 668, 2022).

As timber harvesting operations are planned and executed at the compartment scale, a systematic ground survey across the entire compartment area is likely unfeasible (but see, e.g., Kavanagh, 1984). Our results from examining the efficacy of drone-based surveying provide a robust approach that can overcome limitations of survey area, effort, and safety. These surveys can provide more accurate estimates of local population sizes and the locations of individuals and their home ranges for species with conservation concern such as the southern greater glider and can guide direct home-range protection and detailed information for habitat retention. The drone survey method was developed due to new, strict legal requirements to be able to detect and subsequently protect individuals of threatened arboreal species from timber harvesting. Our research shows that aerial surveys using drones and thermal imagery can achieve these requirements. With the cessation of native timber harvesting in Victoria, the method can find application in species detection and monitoring after other disturbances, for example, after severe fires, to determine management and conservation actions. In cases where precise detection and density estimates are required, spotlighting on foot across smaller areas of the drone survey footprint should still be considered depending on the aim of the survey program or research.

Implications of survey length, study limitations, and future research

Both survey methods recorded more observations when a larger area was surveyed or when surveys took longer to complete. However, southern greater glider observations did not significantly increase with time in both survey methods and more often plateaued as surveys continued into the night (Appendix S1: Figure S5). For survey time in both survey methods, this effect is likely a reflection of the time it takes to record many observations as opposed to few. Therefore, in areas with dense populations or multiple species occupying the same habitat, surveys will generally take longer to complete (Chick et al., 2020). In some cases, this may have led to a decrease in detections over time, as cumulative animal observations during a single survey plateaued. This may indicate that long survey durations may need to be avoided to increase the accuracy of detection and population density estimates via drone (Appendix S1: Figure S6).

As surveys always commenced shortly after dusk, when arboreal species emerge from their dens in tree hollows to forage, the longer a survey continues into the night the higher the chances that some individuals occupying the survey area return to their dens before the drone can make a detection (Kehl & Borsboom, 1984; Lindenmayer et al., 2004). In these cases, this may result in a lower population density estimate for the survey area. Drone surveys may need to be limited to smaller areas or a maximum survey effort of up to four hours after dusk to avoid these confounding issues.

To survey larger areas or areas with dense wildlife populations, survey visits over multiple nights should be used with adjacent areas sampled on successive nights, or multiple drones could be deployed. A drone-based survey method may provide the means for further research into the topic; for example, by conducting repeat surveys with different starting points within the survey area to determine whether detections and subsequent population estimates vary and assess activity patterns of arboreal mammals at a compartment scale.

Operational difficulties, mainly driven by weather conditions, did not allow surveying via drone and spotlighting during the same nights. Therefore, observations of individuals within the different survey footprints of our study are not directly comparable. Arboreal mammals naturally move from night to night depending on home-range size and number of occupied dens (Cunningham et al., 2004; Pope et al., 2004). Studies comparing ground and drone survey results for koalas from the same survey period report that thermal drone surveys generally outperform ground surveys with more detections (Povlsen et al., 2022; Witt et al., 2020). Our approach found, on average, the same number of individuals within the smaller ground survey footprints (Figure 2). Given, however, these may not have been the same individuals, inferences about the performance of either survey method are limited and should be further explored.

While we present evidence that thermal drone surveys are especially well suited to detect dispersed and low-density endangered species populations and their densities, future research has to investigate whether the method can produce reliable long-term monitoring results for areas up to 200 ha, comparable to repeated spotlighting in smaller fixed-area plots (Eberhardt, 1978; Wintle et al., 2005). The same operational difficulties limited the number of repeated drone surveys to only half the compartments targeted ($n = 15$). To validate detectability estimates from this study and derive detection rates for additional species, future work should investigate using, for example, multiple drones and repeating more surveys over the same compartments, as well as testing drone surveys in different environments (e.g., a range of forest types).

Ground surveying was not conducted on separate nights but by two individual observers on the same night. This approach may have led to individuals that were not present on or adjacent to the transect during the surveyed night could be missed meaning that detectability measures will have higher rates of uncertainty. Wintle et al. (2005) have shown that it requires at least three visits to reach around 80% detection probability for southern greater gliders, and even more for common ringtail possums. Therefore, if the aim is to detect most (or all) individuals in an area via walk-spotlighting, double-observer distance sampling during a single night might not achieve this goal. It does, however, produce sound abundance estimates by considering unseen individuals (Burt et al., 2014; Cripps et al., 2021), which we required to conduct the comparisons between drone and spotlighting survey results.

CONCLUSION

Thermal drones are a promising tool for detecting and monitoring nocturnal arboreal mammal populations due to the ability to survey larger areas with detection rates comparable to those from ground surveys. Detailed information on the overall species assemblage and density of different species across a compartment-scale survey area up to 200 ha provides important insights into species occurrence, distribution, and population sizes and status. The ability to survey in areas otherwise inaccessible for surveys on foot will further improve our ability to estimate the populations of species, quantify their recovery following large-scale disturbances, and detect previously undiscovered populations. Importantly, drone-based surveys have the potential to reduce uncertainty in population estimates at the compartment scale and identify the likely home ranges of species with conservation concern for enhanced protection. This can help improve forest management and guide where to support post-disturbance recovery efforts for arboreal wildlife. Future research should investigate the feasibility of thermal drone surveys for long-term species monitoring programs.

AUTHOR CONTRIBUTIONS

Benjamin Wagner and Craig R. Nitschke conceived the idea and developed the methodology for this research with contributions of Sarah W. Garnick and Michael F. Ryan. Joanne L. Isaac and Alana Begg managed and conducted fieldwork and collated ground survey data.

Michael F. Ryan collated and managed drone survey data. Benjamin Wagner analyzed the data and drafted the manuscript with contributions from Craig R. Nitschke. All listed authors contributed to subsequent drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and code (Wagner, 2025) are available in Zenodo at https://doi.org/10.5281/zenodo.15770486.

ETHICS STATEMENT

This research was conducted with an access agreement for parks and reserves from Parks Victoria and a research permit for state forests issued by the Victorian Department of Energy, Environment and Climate Action (DEECA, permit no. 2022-01-25). Surveys for arboreal fauna were conducted with University of Melbourne animal ethics approval (ID no. 2021-22840-21795-2).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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