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RESEARCH ARTICLE

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Using species distribution models and decision tools to direct surveys and identify potential translocation sites for a critically endangered species

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Abstract

Aim: Occurrence records for cryptic species are typically limited or highly uncertain, leaving their distributions poorly resolved and hampering conservation. This can apply to well-studied species, and increased survey effort and/or novel methods are required to improve distribution data. Here, we paired species distribution modelling (SDM) with decision tools to direct surveys for the critically endangered Leadbeater's possum (*Gymnobelideus leadbeateri*) outside its current restricted range. We also assessed survey areas for their suitability to host translocations.

Location: Victoria, Australia.

Method: We used both recent and historic records (now out of range and spatially uncertain) of Leadbeater's possum to build SDMs using MaxEnt. The SDMs informed an initial multi-criteria decision analysis (MCDA) that enabled prioritization of 80 survey sites across seven forest patches (13–145 km outside the known range), which we surveyed using camera traps. Site and vegetation data were used in a post-survey MCDA to rank their potential translocation suitability.

Results: The SDM predictions were consistent with the species' ecology, identifying cold areas with high rainfall that had not recently burnt as suitable. The spatial uncertainty of records did not exert a strong influence on either model predictions or the ranking of patches for surveys. Camera trap surveys yielded records of 19 native species, with Leadbeater's possum detected in only one survey patch, 13 km outside of its previously known range. The post-survey MCDA identified three forest patches as potentially suitable for conservation translocations, and these priorities were not sensitive to the decision criteria used.

Main conclusions: The approach outlined here prioritized survey effort over a large area, resulting in detection of Leadbeater's possum in one new patch. The potential translocation sites identified could present an important risk-spreading measure for the species given the threat posed by bushfire. Combining SDMs and decision tools can help target surveys and guide subsequent conservation strategies.

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KEYWORDS
conservation translocation, ecological niche model, *Gymnobelideus leadbeateri*, habitat suitability model, Leadbeater's possum, prioritization, reintroduction, SDM, threatened species

1 | INTRODUCTION

Knowledge of where species occur underpins most conservation actions and decision-making (Guillera-Arroita et al., 2015). Indeed, resolving uncertainty surrounding species distributions can be one of the most important challenges for the conservation of rare or difficult-to-detect species. Over recent decades, advances in the development of species distribution models (SDMs) have contributed to addressing this challenge (Franklin, 2013). However, despite their promise, a 2013 study found that <1% of published papers using SDMs were specifically targeted at conservation decisions and that SDMs were rarely used within a structured and transparent decision-making process (Guisan et al., 2013).

Correlative SDMs can not only help identify environmental conditions related to species occurrences (Guisan & Thuiller, 2005) but can also generate predictions in new or unsurveyed areas to identify places supporting similar environmental conditions (Elith & Leathwick, 2009). For this reason, SDMs can assist in guiding surveys for threatened and cryptic species, where distributional data may be limited in quality or quantity (Stratmann et al., 2016). For example, Jackson and Robertson's (2011) SDM of a rare and range-restricted subterranean mole guided surveys that detected two previously unrecorded populations. Other studies have looked at SDM predictions beyond species' current known distributions to identify where populations could be reintroduced and/or translocated (Lentini et al., 2018; Payne & Bro-Jørgensen, 2016).

While predictions from SDMs alone can guide surveys or translocations, other considerations including logistical constraints, risks and costs should also be factored into the decision-making process (IUCN/SSC, 2013). To aid transparent decision-making, the predictions from SDMs can be used in decision tools such as multiple criteria decision analysis (MCDA) to help visualize and weigh-up alternative management options, based on stated objectives (Malczewski, 2006). For example, Dade et al. (2014) used MCDA to select sites for assisted colonization of western swamp tortoises (*Pseudemydura umbrina*). Their approach was based on spatial data including suitability predictions from a mechanistic model (Mitchell et al., 2013) and other decision criteria, with weightings assigned by experts.

Given these promising developments and applications, we explored the use of SDMs and decision tools for one of Australia's most threatened species. Once thought to be extinct, Leadbeater's possum *Gymnobelideus leadbeateri* is a small, nocturnal marsupial that was rediscovered in 1961 and is listed as critically endangered by the IUCN (Woinarski & Burbidge, 2016). At the commencement of this study, the species' known range was confined to a 70 × 80 km (or 5600 km^2) region of the Victorian Central Highlands, south-eastern Australia. It occurs predominantly in montane ash (*Eucalyptus regnans/E. delegatensis*) forests, much of which is subject to timber harvesting, and adjacent sub-alpine woodlands dominated by snow gum (*E. pauciflora*). A small, outlying and genetically distinct subpopulation also occurs in lowland swamp forest (Hansen & Taylor, 2008). Subfossil and historical records (pre-1910) indicate that the species once had a much wider distribution—approximately 21,000 km^2 based on the records used in this study, though much of the area between these would have been unsuitable. The contraction of the species' historic range by around 75% is most likely tied to past climactic changes and associated changes in vegetation (Lindenmayer et al., 1991), while current declines are attributed to timber harvesting and large fires (Commonwealth of Australia, 2016). The vast nature of the Leadbeater's possum's historic range has triggered suggestions that there may yet be undiscovered populations (Harley, 2004). A substantial range extension or discovery of new populations could have implications for future conservation actions for the species.

Previous studies have attempted to locate new populations of Leadbeater's possum—mostly in montane ash forest—however, all failed to do so (reviewed in Harley, 2004). These surveys employed traditional survey methods (e.g. spotlighting) that do not reliably detect the species (Nelson et al., 2017). Motion-heat triggered cameras (also known as camera traps) have recently emerged as a highly effective method for detecting the species and can be deployed to survey large areas (Harley et al., 2014; Nelson et al., 2017).

There are innate risks for range-restricted species that occur in disturbance-prone landscapes, particularly in areas prone to catastrophic events such as bushfire that can reverse gains made through long-term conservation efforts. Creation of additional geographically distinct populations of Leadbeater's possum through conservation translocations could act as a risk-spreading strategy against this threat and has been identified as a management option to reduce the likelihood of extinction (Commonwealth of Australia, 2016). Given the extensive area that encompasses the historic range of the species, an inherent challenge is how to identify suitable translocation sites. Prerequisites would include the presence of suitable habitat, an adequate separation from current populations to reduce the risk of all being impacted by a single fire event, and various logistical criteria relating to field operations and monitoring.

In light of these challenges, here we use the Leadbeater's possum as a case study to demonstrate the potential value of (i) pairing SDMs and decision tools to direct surveys for rare and difficult-to-detect species, in this case outside of its current known distribution; and (ii) using these approaches to also identify sites that may be suitable for potential conservation translocations. Locating or establishing new populations of Leadbeater's possum outside of Victoria's Central Highlands would constitute a critical action for improving the long-term conservation of this range-restricted threatened species.

2 | METHODS

Our study consisted of four main steps or components: (1) species distribution modelling (SDM), (2) survey patch selection/multiple criteria decision analysis (MCDA), (3) ground-truthing, site selection and camera trapping and (4) conservation translocation prioritization (see Figure 1 for workflow). In brief, we first developed presence-background SDMs for Leadbeater's possum and conducted a suite of sensitivity analyses relating to (a) the spatial uncertainty of some of the records, (b) the inclusion of different predictor variables in the models, (c) methods used to select background points and (d) the uncertainty of the resulting model predictions. Then, using the predictions from the models, we identified patches of contiguous, suitable habitat that were most likely to support undiscovered populations of Leadbeater's possums or which could act as potential future translocation sites. We decided on which of the patches to survey by ranking them, using a spatially explicit MCDA, and checking the sensitivity of the resulting rankings to the weightings assigned to the decision criteria. Third, we ground-truthed a sub-set of the highest ranked patches and installed motion-heat sensor camera traps where there was suitable habitat. Finally, to prioritize sites for potential translocations, we undertook a second MCDA using spatial data and vegetation data collected at survey sites. Further details as to how each of these steps was implemented are provided below.

2.1 | Species distribution modelling

To identify potentially suitable habitat for Leadbeater's possum, we constructed presence-background SDMs. We obtained 1845 occurrence records of the species from a range of sources (Victorian Biodiversity Atlas = 1124 [downloaded 31/03/2017], Arthur Rylah Institute for Environmental Research = 348, Zoos Victoria = 323, VicForests = 50), which included a substantial number of spatial duplicates. We sequentially assessed pairs of records that were spaced <500 m apart (based on the average size of a Leadbeater's possum's territory; Harley, 2005; Smith, 1984) and at each iteration retained the record with greater spatial accuracy. This yielded a data set of 581 unique occurrences used for modelling, including historic and sub-fossil records.

Some of the records used to build the SDMs had high reported spatial uncertainty (up to 18 km), which can lead to spurious environmental correlations and predictions of suitability (Naimi et al., 2014). However, we wanted to retain these records as some captured parts of the Leadbeater's possum's previous geographic range (and possibly environmental space) that was not represented in other data. Hence, we tested the sensitivity of our patch rankings to this spatial uncertainty by taking the 246 records that had uncertainty ≥1 km and resampling ten points from within a buffer equal to each record's uncertainty (Hill et al., 2012). This resulted in 10 new data sets containing 246 resampled "uncertain" points and the remaining 1599 "certain" records. We repeated the filtering, modelling and ranking process for each data set, using the resulting predictions and associated patch rankings to assess the influence of any changes to the model outputs.

We selected 14 candidate predictor variables to reflect the habitat and environmental requirements of Leadbeater's possum (Table S1). To produce indices of vegetation relevant to the possum, we summed SDMs (provided by Matt White, Arthur Rylah Institute, unpublished data) representing predictions of the historic occurrence of eucalypt species used by Leadbeater's possum ("eucalypt index" hereafter; *E. regnans*, *E. nitens*, *E. delegatensis*, *E. denticulata*, *E. ovata*, *E. camphora* and *E. pauciflora*) and species that provide mid-storey connectivity ("mid-storey vegetation index": *Leptospermum*

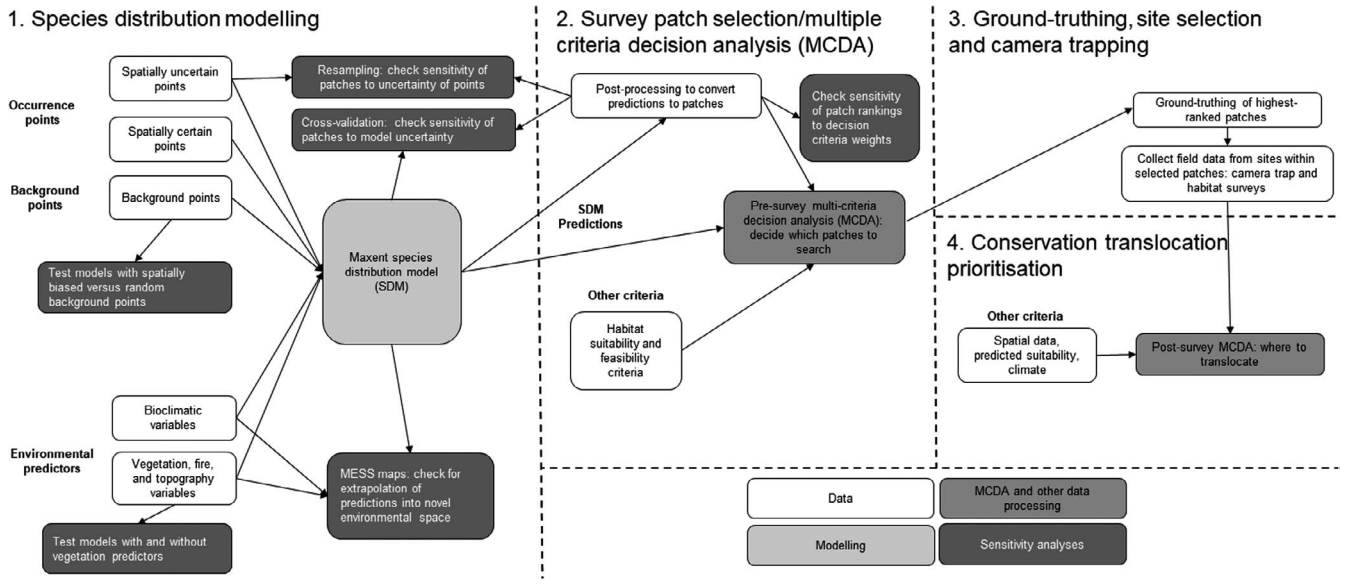


FIGURE 1 An overview of the study design across four stages: 1. species distribution modelling, 2. survey patch selection and multiple criteria decision analysis, 3. ground-truthing, site selection and camera trapping and 4. conservation translocation prioritization, including associated sensitivity analyses

grandifolium and *Nothofagus cunninghamii*). This resulted in two indices (mid-storey and eucalypt index) of the historic occurrence of areas supporting suitable floristic composition for Leadbeater's possum. We calculated time since fire at each occurrence point as the difference between the year of the record and the year of the most recent previous fire in that location. We removed highly correlated predictors (Pearson's correlation coefficient >0.7; Merow et al., 2013) and those that represented similar drivers (e.g. slope and topographic wetness), by selecting the layer with greatest ecological relevance. The final layers used for modelling were as follows: temperature seasonality (BIO4), maximum temperature of the warmest month (BIO5), minimum temperature of the coldest month (BIO6), annual precipitation (BIO12), topographic wetness index, time since fire, mid-storey vegetation index and the eucalypt index (Table S1), and variables were resampled to a 250 m × 250 m resolution using the resample function (in the raster package R version 3.4.2).

We built presence-background SDMs for Leadbeater's possum and generated predictions using MaxEnt (Phillips et al., 2006) in R (version 3.4.2, R Core Team, 2016) with the package "dismo" (Hijmans et al., 2017). MaxEnt is a machine learning-based method (Phillips et al., 2006) that performs well with presence-only data relative to other methods (Elith et al., 2006), and is equivalent to Poisson point process models (Renner & Warton, 2013). Background data provide information about the range of environmental conditions available in a sampled region and can be used to account for biases that are common in presence records (Phillips et al., 2009). We restricted our background points to fall within 5 km of Leadbeater's possum records, as previous surveys for the species often focused on areas within the vicinity of known locations (Nelson et al., 2015, 2017). There are also known survey biases towards roads, so we used a raster representing the inverse distance to roads to weight the selection of 10,000 background points. To remove bias in the fire history of background points, we ensured the time since fire of background points reflected the fire history of the landscape over the period that the presence records were collected (rather than the landscape's current fire history). To do this, we assigned each background point a time since fire drawn from the distribution of fire ages of the Leadbeater's possum records.

We modelled and generated predictions of suitable habitat across all five bioregions (Department of the Environment, 2012) where Leadbeater's possums have been detected (current and historic records), as well as 18 neighbouring bioregions (Figure 2). To avoid over-fitting, which can result in predictions that reflect idiosyncrasies in the data rather than ecological requirements of the species (Elith & Graham, 2009), we increased regularization to a beta value of two for hinge, categorical, linear and quadratic features and switched off threshold and product features (Merow et al., 2013). We evaluated models using tenfold cross-validation, using AUC as a metric of model performance, and assumed that an AUC of 0.7–0.8 indicated "Acceptable discrimination," an AUC between 0.8 and 0.9 would indicate "Excellent discrimination," and AUCs ≥0.9 were for models of "Outstanding discrimination," following Hosmer and Lemeshow (2000). We also checked the 10 predictions resulting from the cross-validation against our main analyses to see how much model uncertainty could influence our inference, and estimated the degree of correlation between the predictions using the Pearson statistic. Following this process, we used all 581 unique records to generate the final predictions, using the default cloglog output for all subsequent analyses.

To examine the influence of decisions made during the modelling process, we produced variants of the SDM for Leadbeater's possum created: (i) with and without vegetation predictors, as these were based on historic vegetation cover and thus may not reflect current vegetation, and (ii) with randomly selected, and then biased background points. We tested for extrapolation into novel environmental space using multivariate environmental similarity surface maps (MESS) that measure the similarity between the training data set and the projection data set (Elith et al., 2010).

2.2 | Survey patch selection/multiple criteria decision analysis (MCDA)

The area encompassing historic records of Leadbeater's possum is vast, so we prioritized survey efforts in patches that were most likely to contain both suitable habitat and undiscovered populations. We chose to focus searches only on sub-alpine woodlands and lowland swamp forests, because montane ash forests have been highly disturbed by bushfires and timber harvesting (Lindenmayer et al., 1991) and have been the focus of most previous surveys for the species. They are also tall and widespread, making targeted camera trap surveys logistically challenging. Conversely, sub-alpine woodlands and lowland swamp forests occur in localized patches, have a lower canopy that brings animals to a more easily accessible height for camera trapping and are less disturbed so may have provided refuge habitat for remnant populations. The ecotone of sub-alpine woodland and montane ash forest was also surveyed where it occurred along gullies with montane riparian thickets. We took the SDM predictions and excluded the species' current known distribution, as well as areas that were unlikely to support Leadbeater's possums or the target habitat types because they were severely burnt in the ten years preceding the field sampling in 2017, did not contain native vegetation or were over 5 km from target ecological vegetation classes (EVCs). The target EVCs were Swampy Riparian Complex, Swampy Riparian Woodland, Swampy Woodland and Montane Riparian Thicket. We then calculated the minimum model prediction value that captured 95% of (i) all of the Leadbeater's occurrence records and (ii) lowland records only, and applied the thresholds to sub-alpine (1000–1600 m elevation) and lowland (<500 m elevation) areas, respectively. In this binary habitat-non habitat map, cells within 500 m of each other were grouped and assigned as potential survey "patches."

We ranked the survey patches using swing weighting (Dieter & Schmidt, 2009), a form of MCDA that is explicit and easily adjustable. For our MCDA, we used criteria in three categories: (i) the relative suitability predicted by the SDM, (ii) other measures of habitat

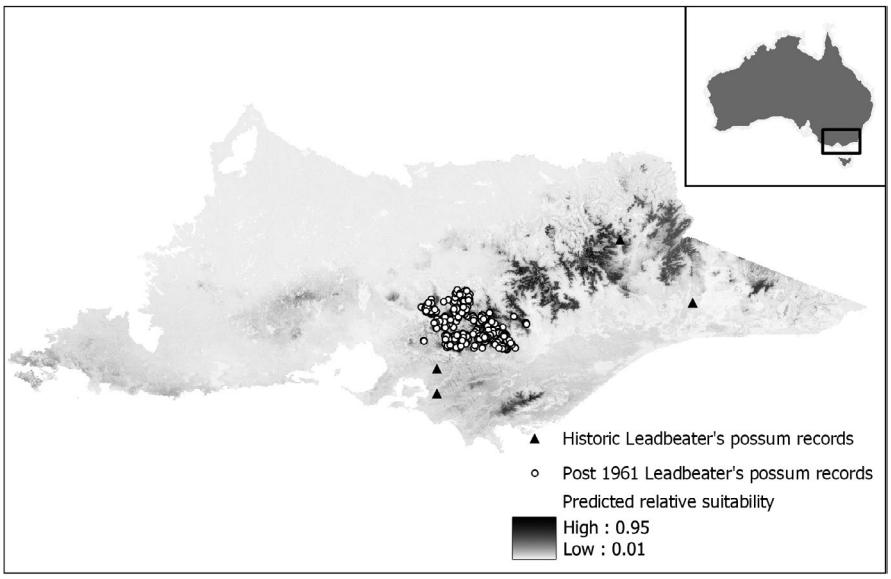


FIGURE 2 Predicted relative habitat suitability for Leadbeater's possum across the study region (bioregions containing records plus neighbouring bioregions), based on a presence-background SDM. White points represent Leadbeater's possum records collected after 1961, and black triangles represent historic (pre-1961) and sub-fossil records of Leadbeater's possum. Insert shows the location of the study region within Australia

suitability (e.g. length of watercourses in a patch), and (iii) survey feasibility (Table S2). These criteria and weightings were developed based on knowledge of the species' ecology and management objectives. We first calculated the contributions of each weighted criteria based on normalized values (Table S2), where a higher value represented a positive influence. Where a lower value was more optimal, we calculated one minus the normalized value. These contribution values were then multiplied by the weighting of that criteria and divided by the sum of all weightings. When the contributions of each criterion were summed, the resulting value (decision score) equalled one for a patch that had the best measurement for all criteria. Patches were ranked based on these decision scores to inform which patches would be selected for surveys.

We also examined the sensitivity of patch rankings to the criteria weightings assigned in the MCDA, as these weightings represent subjective decisions and management priorities may shift over time. We resampled the weightings 1000 times, each time randomly assigning each criterion a score between 0 and 100, and the patches were re-ranked. We then calculated the mean and standard deviation of these rankings to assess sensitivity to weightings.

2.3 | Ground-truthing, site selection and camera trapping

Patches identified through the SDM-MCDA process ranged in size from 66 to >500,000 ha. We used the rankings to select a sub-set of patches ($n = 7$) to ground-truth and also selected five additional patches based on the recommendation of ecologists and land managers familiar with the regions of interest ($n = 4$), or the presence of historic records ($n = 1$; although this patch was also ranked 12th in the MCDA).

While ground-truthing, we avoided areas that had been recently (<10 years) burnt at moderate–high severity or had been recently harvested for timber. We selected survey sites that were separated by a distance >500 m, except where there was localized high-quality habitat that warranted extra survey effort, including where a barrier (e.g. track or vegetation change) necessitated closer site spacing to adequately sample the area.

At each survey site, we installed two Reconyx motion sensor cameras (models HC500, HC600 or PC900) up to 100 m apart in areas with high vegetation connectivity, at a height of 1–4 m. A bait station made of PVC pipe and wire mesh (Figure S1) filled with creamed honey was placed on a tree 0.5–3 m from each camera. To maximize trigger frequency, we rotated cameras 90° from their normal orientation (Harley et al., 2014). Cameras were primarily deployed for four to six weeks (between 25 September 2017 and 23 February 2019) to achieve a high detection probability (>0.80; Nelson et al., 2017). Three cameras failed before the end of the survey period due to battery failure; however, at each of these sites, the second paired camera worked for the full survey period. Cameras in one survey patch, Red Robin Battery, were deployed for 14 weeks due to limited site accessibility.

2.4 | Conservation translocation prioritisation

We conducted vegetation surveys at each camera trapping location (see Appendix S1 for full details of vegetation surveys) to inform a second MCDA to rank potential translocation sites for Leadbeater's possum, following the approach of Dade et al. (2014; Figure S3). Camera sites that fell within 730 m of each other (half the species' maximum recorded dispersal distance; Harley, 2005) were grouped into "clusters," and these formed the basis of the ranking process. This approach enabled identification of a network of release sites within which translocated individuals could disperse and breed. The decision score for each camera location was calculated based on four broad criteria: (1) modelled relative suitability, (2) local habitat variables, (3) area and habitat extent and (4) potential threats (see Appendix S2 and Figure S3 for a

detailed description and diagram of criteria). Based on these criteria, we ranked the camera locations (1–160), and the reverse of those rankings became the "score," such that a good location had a higher score. Each cluster was assigned the summed scores for the camera locations it comprised, which resulted in a high ranking for large clusters that contained multiple highly ranked camera locations while not penalising for a small number of low-ranked camera locations.

Clusters were ranked using the swing weightings approach described above, with equal weighting applied to each criterion. We compared the cluster rankings from the full MCDA against rankings based on the SDM predictions only, and the SDM predictions and local habitat variables.

3 | RESULTS

3.1 | Species distribution modelling

Areas predicted to be highly suitable for Leadbeater's possum by the SDM corresponded with places that had high modelled presence of key eucalypt species and mid-storey vegetation, were wet (high annual precipitation and topographic wetness index), had not recently burnt (>15 years), had low seasonal temperature variation, and low temperatures in the warmest and coldest months (Figure 2; Figure S4). The ten-fold cross-validation yielded an AUC of 0.766 (standard deviation 0.027), and there was high correlation between the ten predictions resulting from this process and the main model predictions (ranging from 0.992 to 0.998, see Figure S5). The MESS maps indicated there were some areas of extrapolation within survey patches, generally towards the edges of the study region (Figure S6). Extrapolation within and near survey patches stemmed from some areas being more seasonal than the training data as well as areas where minimum monthly temperatures were considerably colder (down to −7.1°C) than the coolest temperatures in the training data (−2.2°C). There was also extrapolation to areas that were longer unburnt than the training data (>115 years). In reality, this suitability may be affected by mid-storey senescence in montane ash forest. The survey patches produced from model variants which did not include vegetation variables or account for biases in the background points did not differ substantially from the model which did (Figure S2). Given that the patches produced showed little sensitivity to the inclusion of these variables, we chose to base patch selection on the model that included both in subsequent steps and for the results reported below.

Based on the resampling of the spatially uncertain points from within their uncertainty buffers, six of the top eight patches always remained ranked in the top eight, and the two patches that dropped out of the top eight had dropped to ninth rank once and twice, respectively. Because the sensitivity analyses indicated that neither changes to criteria weightings nor the uncertainty of point locations would change where we ground-truthed, we chose to proceed as planned based on the main analysis.

3.2 | Survey patch selection/multiple criteria decision analysis (MCDA)

From the model predictions, we identified 34 sub-alpine woodland patches, and 392 lowland swamp forest patches containing potentially suitable habitat outside Leadbeater's possum's core range in the Central Highlands (Table S3). Although patches in lowland areas were more numerous than sub-alpine woodland, they had lower median relative suitability (0.13 vs. 0.41) and were smaller (median area 330 ha vs. 6535 ha), and so were considered less likely to support extant Leadbeater's possum populations.

The sensitivity analyses indicated that the highly ranked patches tended to remain highly ranked regardless of the weightings assigned to the criteria in the MCDA (Figure 3). Spatially uncertain points did not appear to have a strong influence on model predictions, and the use of the resampled points did not result in substantial changes in the location or rank of survey patches, particularly those that were mostly highly ranked (Figure 4).

3.3 | Ground-truthing, site selection and camera trapping

A total of 12 patches were ground-truthed, four of which were selected based on the recommendation of ecologists and land managers and one based on the presence of historic records (Figure 5). During ground-truthing, we identified 80 sites (160 camera locations) from seven patches where there was sufficient high-quality habitat to warrant surveys (Figure 5). Sufficient high-quality habitat was not found in five other ground-truthed patches of lowland swamp forest. No lowland patches of sufficient size and quality were identified to warrant surveys in this study (hence they are not included in Figure 3).

Leadbeater's possums were detected in one of the seven patches surveyed (four out of 80 camera trap sites; Figures 5 and 6). The patch where we detected the species was the closest surveyed patch to the species' current known distribution. These new records were 13 km from the nearest previous record, though there are now additional records in this area (McBride et al., 2019). The camera traps captured 386,091 photos (Table 1) over 6620 trapping nights.

In addition to Leadbeater's possum, we detected seven other species of mammal (the most common being agile antechinus and feathertail glider, both detected at 44 of 80 sites) and 11 bird species (Table 1).

3.4 | Conservation translocation prioritisation

Regardless of whether the translocation rankings were based on (i) all criteria, (ii) the SDM only or (iii) the SDM and local habitat variables, the highest and lowest ranked clusters generally remained the same (Figure 7). However, for a few clusters, such as cluster 10 (Wentworth), there was substantial variation between the rankings when using different criteria; the high ranking for this cluster when

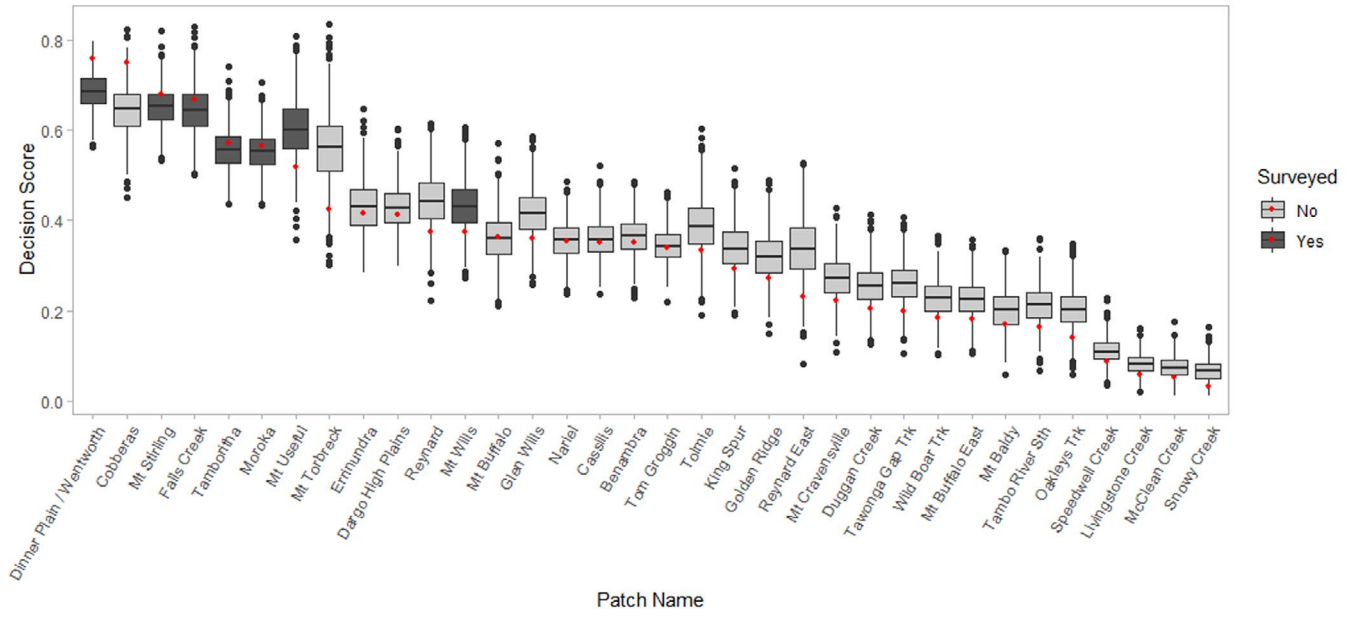


FIGURE 3 Box plots showing the range of decision scores for patches of Leadbeater's possum habitat (excluding lowland sites), when decision criteria weightings were resampled 1000 times. Dark grey boxes indicate surveyed patches, and red dots represent the decision score/weightings that were used in the final MCDA

all criteria were used was likely due to the low search effort that was required to find high-quality habitat.

In terms of suitability for translocation, the highest ranked clusters in sub-alpine woodland were within the Mt Stirling, Moroka and Dinner Plain patches (Table S4). These clusters were ranked highly for different reasons. For example, cluster 12 (Mt Stirling) was the highest ranked due to its large size, high annual precipitation and suitable vegetation measures (Table S4). In contrast, cluster 4 (Moroka) ranked highly due to the low search effort required to find high-quality habitat, the land tenure index and high vegetation connectivity (Table S4).

4 | DISCUSSION

This study demonstrates the power of combining advances in ecological modelling and survey techniques with decision science to inform conservation actions for a critically endangered species. Using SDMs and decision tools, we were able to efficiently locate habitat and direct surveys for Leadbeater's possum across a broad geographic region outside of its known range. By ground-truthing model predictions and exploring sources of uncertainty via sensitivity analyses, we ensured that our results could reliably be used to inform conservation decisions for this species. Although the potential to use SDMs to guide surveys for rare species has been highlighted in the literature for some time (e.g. Le Lay et al., 2010), there are still surprisingly few published examples where surveys have been conducted subsequent to modelling (reviewed in Fois et al., 2018). Studies that have undertaken field surveys typically rely solely on the model predictions to direct searches. Where other considerations (such as survey feasibility) have been incorporated, it is often through an unstructured approach. Our aim is that, by providing clear detail of both the methods we have used and the advantages that these afford, relative to more traditional and less-structured techniques (i.e. improved efficiency, and in turn more resources for management interventions), practitioners will more readily adopt systematic and transparent decision-making in field survey design.

Using SDMs and decision tools, we were able to efficiently target surveys for Leadbeater's possum across a broad geographic region outside of its current known distribution. Despite the presence of suitable habitat, subsequent camera trapping detected Leadbeater's possum in only one of seven forest patches surveyed. The patch where we detected the species was the closest to the species' known range, and represented a 13 km range extension. Since this project commenced, additional records have been obtained from this area (McBride et al., 2019; Arthur Rylah Institute, unpublished data). Notably, one of the four camera trapping sites where we detected the species was designated for timber harvesting. In response to our observations, a conservation buffer has been applied around each location by the land management agency.

Our study represents an important first step towards the identification of potential translocation areas for this species using a transparent, repeatable framework. Given the risk posed by large bushfires, conservation translocations are likely to be a key conservation strategy for both the range-restricted highland population of Leadbeater's possum and the genetically distinct lowland population that is confined to a single locality. Rankings of survey sites for potential translocations were consistent, irrespective of the decision criteria used, and this adds confidence to our conclusions. However, translocations are far from trivial interventions, and further assessments of important site-level considerations (e.g. predation, competition) are required prior to implementation (Banks et al., 2002; Schwartz & Martin, 2013). It is also worth noting that despite

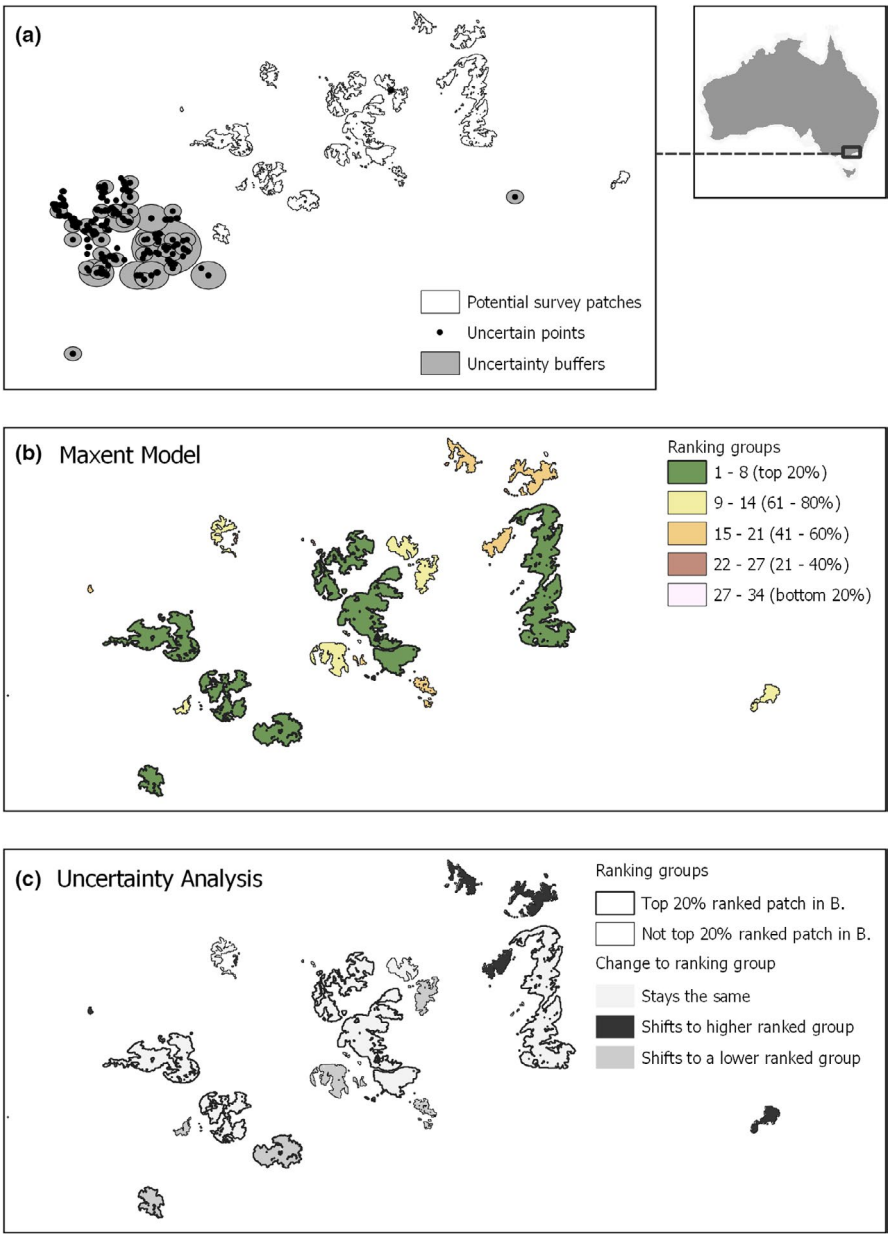


FIGURE 4 (a) Leadbeater's possum records (black) used in sensitivity analyses of spatial uncertainty: uncertainty is indicated by grey buffers. (b) Ranking of survey patches based on pre-survey MCDA. (c) Maximum change in the ranking of survey patches in the sensitivity analyses of spatial uncertainty

substantial search effort, we were unable to locate any large areas of suitable lowland habitat within the areas modelled, and the likelihood of undiscovered lowland populations beyond the current range appears low. Future translocations involving the lowland population may require habitat typical of the highland population.

When using species distribution models to inform real-world decisions, it is particularly important to investigate sources of uncertainty and extrapolation that can influence predictions (Hill et al., 2012; Naimi et al., 2014). A key risk when predicting outside of a species' range is that this may require extrapolation into novel environments that are not represented in training data (Elith & Leathwick, 2009). The MESS map (Figure S6) indicated a few small areas of extrapolation within the survey patches where the SDM may have over-predicted habitat suitability in very cold or long-unburnt forest. Spatially uncertain occurrence records can also be problematic, as these can obscure or distort species–environment relationships (Naimi et al., 2014), but we found that this did not have a strong influence on the areas we selected to survey. This was likely due to the continuous nature of most of the predictor variables, which spanned broad spatial scales. Nevertheless, the approach we took to testing the sensitivity of the models to spatial uncertainty meant that we could confidently include historic records that would have otherwise been omitted, and which came from areas well outside the Leadbeater's possum's current geographic range.

Although we failed to detect Leadbeater's possum in six of the seven patches surveyed, the results provide valuable absence data that help resolve the distribution of this critically endangered species. We focused here on maximising our chances of detecting Leadbeater's possum and identifying high-quality habitat and thus surveyed only highly ranked patches. If our primary objective had instead been to test and improve the model, we would have surveyed patches with a range of predicted suitability values, focusing

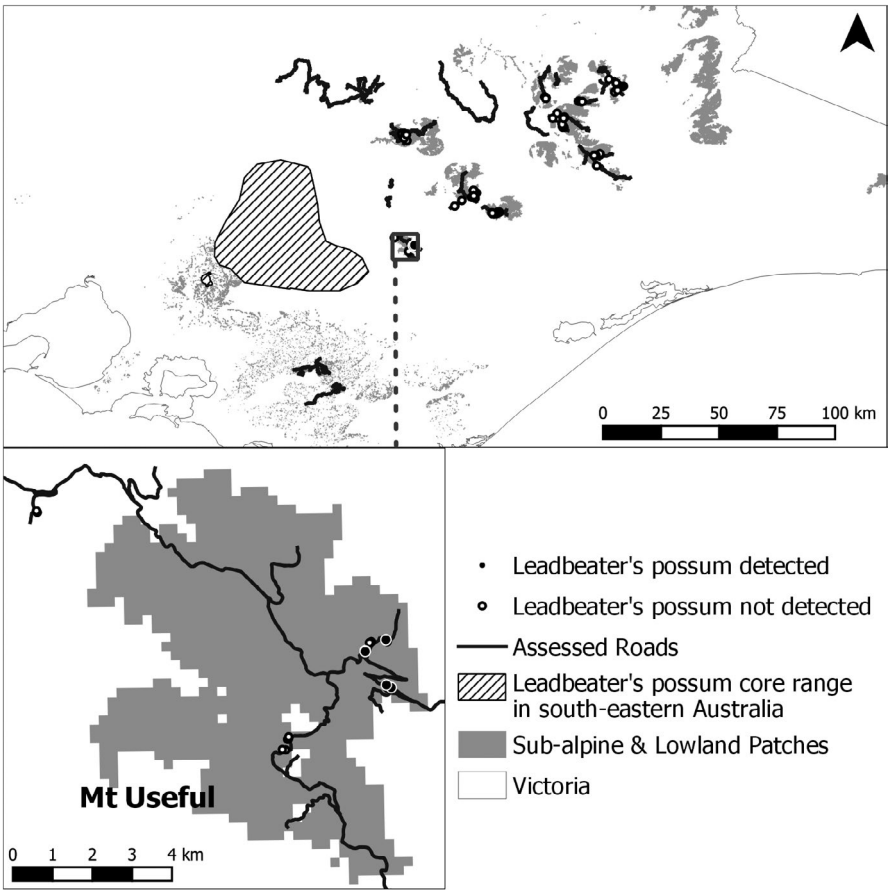


FIGURE 5 Patches outside of the Leadbeater's possum's known range that were ground-truthed for suitable habitat, including sub-alpine and lowland patches predicted by our models (shown in grey), roads where adjacent habitat was assessed for suitability (—) and camera sites where Leadbeater's possums were detected (•) and not detected (○). Insert shows the patch where possums were detected (Mt Useful) in more detail. The four patches selected for ground-truthing based on recommendations of ecologists and land managers are shown as the assessed roads that fall outside of the shaded patches



FIGURE 6 Camera trap image of a juvenile Leadbeater's possum captured 13km from the species previously known range

on areas where a new presence or absence would provide the most valuable information to improve the model (Canessa et al., 2015). Nevertheless, the inclusion of the absences from our surveys may improve future SDMs of this species. Where data are available, it is generally preferable to adopt a presence–absence framework for SDMs as these models can yield predictions of probability of occurrence rather than relative likelihood of occurrence and are less sensitive to survey biases (Guillera-Arroita et al., 2015). In this study, we were interested in the ranking of sites rather than absolute values, so estimates of relative likelihoods were adequate. Our modelling approach, using presence-only data, is also less vulnerable to the effects of imperfect detection, making it a suitable option for this difficult-to-detect species.

Another persistent challenge when modelling species' distributions is that spatial data often have poor resolution relative to the scale of the variables of interest, resulting in models that predict well across broad areas but perform poorly for fine-scale, site-level attributes (Austin & Van Niel, 2011). In cases such as ours, where we are fitting models with quite old (but potentially valuable) records, environmental data need to be available for both the period when the data were collected for modelling and the present day for predictions. In this example, we know that the presence of key eucalypt species and mid-storey vegetation is important to Leadbeater's possum (Smith & Lindenmayer, 1988). Models of these key floral species were included in our SDM; however, our modelled patches were overly inclusive and contained areas that did not support these features. One option may be to use the SDM-MCDA approach described here and, where available, include high-quality remotely sensed data such as LiDAR (Jiang, 2019) to further refine selected patches.

TABLE 1 The distance ground-truthed, the number of sites, cameras, photographs, sites with Leadbeater's possum detections and number of other species identified in each survey patch

Patch name	Length of roads ground-truthed (km)	Number of survey sites (cameras)	Number of camera trap photos	Number of sites where Leadbeater's possums were detected	Number of native bird and mammal species identified
Dinner Plain/ Wentworth	116.35	25 (50)	110,661	0	13
Moroka	19.85	10 (20)	89,851	0	10
Mt Stirling	90.63	11 (22)	21,664	0	9
Mt Useful	49.68	8 (16)	27,441	4 (5 cameras)	7
Mt Wills	59.03	11 (22)	51,268	0	10
Red Robin Battery	30.01	3 (6)	1,211	0	7
Tamboritha	44.62	12 (24)	83,995	0	12
Total	410.17	77 (154)	386,091	4	19

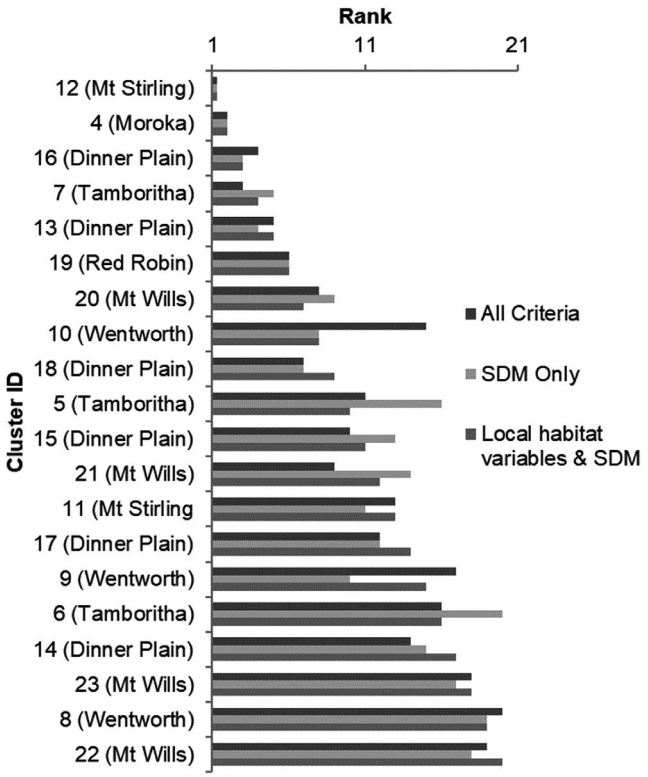


FIGURE 7 Ranking of potential conservation translocation clusters based on all criteria (dark grey), the SDM only (light grey) or both the SDM and local habitat variables (grey). Clusters were each given an ID number. The survey patch to which each cluster belongs is named in brackets. Most survey patches contained more than one translocation cluster

In spite of the challenges in both modelling the habitat of Leadbeater's possum and managing the species, our study represents a powerful illustration of the benefits of combining SDMs and decision tools, including thorough explorations of uncertainty. Using SDMs within a clear and transparent decision-making framework, we were able to efficiently improve our knowledge of the distribution of this critically endangered species and its habitat across south-eastern Australia—including identifying potential translocation sites. Such knowledge is critical for robust and effective conservation strategies aimed at supporting its long-term persistence.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

As this species is critically endangered, records of its location constitute sensitive information. Most of the records presented in this paper are available from the Victorian Biodiversity Atlas (vba.dse.vic.gov.au); however, records owned by Zoos Victoria that relate to ongoing monitoring of nest boxes represent sensitive sites and cannot be made public. In lieu of coordinates for species records, presences and absences with corresponding environmental covariates are available. All other data and code associated with

this manuscript are available via Dryad [https://doi.org/10.5061/dryad.6q573n603].

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SUPPORTING INFORMATION

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