Using a Species Distribution Model to guide NSW surveys of the Long-footed Potoroo (*Potorous longipes*)

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Abstract

Knowledge of threatened species' distributions is essential for effective conservation decision-making. Species distribution models (SDMs) are widely used to map species' geographic ranges, identify new areas of suitable habitat and guide field surveys. In New South Wales (NSW), Australia, there are grave doubts about whether populations of the Critically Endangered long-footed potoroo (*Potorous longipes*) remain extant, and identification of occupied sites is a high priority for its conservation. We used an SDM (Maxent) to identify regions in NSW that may have suitable habitat for the potoroo. The SDM was built with seven climate layers and had strong predictive performance (cross-validated AUC = 0.94). We then combined this information on habitat suitability with vegetation and topography, to identify 58 survey sites across NSW. From April 2016–May 2017, we undertook six field trips deploying six to eight cameras at each site for 52–63 days, resulting in 25,120 camera trap nights. A total of 215,759 images captured 43 native and feral animal species, but no long-footed potoroos. Following the survey, newly available, independent presence and absence data were used to validate our model. A Kruskal-Wallis H Test indicated that habitat suitability values were significantly higher at presence locations than absence locations ($H=58.66$, $DF=1$, $P<0.001$). Finally, we refitted the Maxent model with the new data, and identified additional regions that future surveys could explore. We conclude, however, that if the long-footed potoroo remains extant in NSW, it is extremely rare.

Keywords: Species distribution model, Maxent, conservation biology, presence-only model, threatened species.

32 INTRODUCTION

33 Surveys for rare and threatened species are essential for monitoring populations and
34 supporting conservation outcomes. However, knowing where to direct survey effort is often
35 hampered by a paucity of data regarding species' distributions, biology and ecology.
36 Species distribution models (SDMs) provide an approach to mapping potentially suitable
37 habitat to guide field surveys (Aizpurua *et al.* 2015) and have been used in this manner for
38 a variety of taxa, including marine invertebrates (Rooper *et al.*, 2016), amphibians (Groff *et*
39 *al.* 2014), reptiles (Stratmann *et al.* 2016), birds (Aizpurua *et al.* 2015) and mammals
40 (Lumsden *et al.* 2013). The application of SDMs is appealing as it is efficient (e.g. relative
41 to random sampling, Guisan *et al.* 2006) and research has demonstrated that the
42 detection of rare species is greatly improved when surveys are guided by SDMs (Guisan
43 *et al.* 2006, Le Lay *et al.* 2010).

44 The long-footed potoroo (*Potorous longipes*) is a small marsupial rat kangaroo (1.5–2.3
45 kg) (Scotts & Seebeck 1989) listed as Endangered in Australia (Environment Protection
46 and Biodiversity Conservation Act 1999). Rare and elusive, it was described as a separate
47 species in 1980, having previously been considered to be the more broadly distributed,
48 vulnerable, long-nosed potoroo (*P. tridactylus*) (Seebeck & Johnston 1980). Since then,
49 three small, disjunct populations have been located: two in north-eastern Victoria
50 (Department of Sustainability and Environment (DSE) 2009), and one in south-eastern
51 New South Wales (NSW) (National Parks and Wildlife Service (NPWS) 2002). The
52 recently updated IUCN listing estimates that no more than a few thousand individuals
53 remain (Woinarski & Burbidge 2016).

54 The long-footed potoroo has been found across various ecological vegetation classes,
55 altitudes (150–1370m), topographic types (from creeks to ridge tops) and forest age
56 classes (e.g. eight-year regrowth post-timber harvesting to old growth forests) (Scotts &
57 Seebeck 1989; Green *et al.* 1998; Chick *et al.* 2006; Elsner *et al.* 2012). Its home range is
58 estimated to be 14–100ha (Green *et al.* 1998; DSE 2009), with preferred areas having
59 moist soils and sheltered aspects, likely due to the species' relationship with fungal food
60 sources (DSE 2009; NPWS 2002). Indeed, the long-footed potoroo is the most fungi-
61 dependent mammal in Australia: on average, 91% of its diet comprises truffle-like fungi,
62 with the remainder consisting of invertebrates and plants (Green *et al.* 1999). As such,
63 year-round fungal abundance and diversity is likely a key requirement for the distribution of
64 this species (NPWS 2002).

65 All records of long-footed potoroos in NSW occur within the boundaries of the South-East
66 Forests National Park (SEFNP) (Figure 2). Multiple intensive surveys have been
67 undertaken in NSW to evaluate the species' distribution and patterns of occupancy. Hair
68 tubing and scat surveys in 1986 and 1989 confirmed the presence of the species within
69 the Sheep Station Creek catchment of SEFNP (Claridge 2002; NPWS 2002). These
70 records, together with records from Victoria, were used to calibrate a BIOCLIM SDM, the
71 results of which informed extensive live-trap and hair tube surveys conducted between
72 1990–1995 (Claridge 2002, Nix 1986) The surveys, however, yielded fewer than
73 seventeen definitive records, with no live captures or direct observations made (Claridge
74 2002, NPWS 2002). The most recent survey undertaken in 2008/09 used scat searches,
75 hair tubes and low-intensity camera trap surveys and yielded no new findings (unpublished
76 data, J. Bentley).

77 In Victoria, however, recent camera surveys for the long-footed potoroo have had
78 considerably more success. A multi-year survey program (2011–2016) detected
79 individuals at 13 sites (pers. comm. Marc Perri, DELWP 21 February 2017), including a
80 new population in the Gippsland area west of the Snowy River (Lumsden *et al.* 2013). In a
81 separate study, predictions from an SDM guided a 2012 survey for the species in
82 Gippsland, with long-footed potoroos detected at 41 sites (Lumsden *et al.* 2013). Of these,
83 12% were outside the previous known range of this species (Lumsden *et al.* 2013). In
84 addition to the extension of surveys into new areas, other factors may have contributed to
85 increased detection of the potoroo, including an increase in potoroo numbers resulting
86 from improvements in predator control (fox baiting) and habitat recovery following the
87 Millennium Drought (2002–2010). Most recently, camera surveys undertaken in 2016, as
88 part of the Southern Ark Program (monitoring fox control) in Victoria, gave rise to 67 new
89 detections across 35 locations (pers. comm. Andy Murray, DELWP, 1 December 2016).

90 In contrast, the failure of additional surveys to detect the species in parts of NSW where it
91 was previously found raises concerns about possible extinction in the state. These
92 concerns are echoed in the decision to upgrade the species' conservation status in NSW
93 to Critically Endangered (NSW Scientific Committee (NSW SC) 2015). Alternatively, these
94 findings might suggest: 1) surveys did not reliably census the species in this region, 2) the
95 long-footed potoroo is present at extremely low densities, or 3) sampling occurred in the
96 wrong locations.

97 Since the original BIOCLIM model was constructed, the species has been detected in new
98 areas in Victoria, expanding the long-footed potoroo's distribution and resulting in the

discovery of populations in new habitat types, e.g. drier coastal (Cape Conran) and hinterland habitat (Lumsden *et al.* 2013; Elsner *et al.* 2012). Furthermore, additional environmental datasets have become available, and SDM techniques (e.g., Maxent: Phillips *et al.* 2006; Elith *et al.* 2006; Merow *et al.* 2013) have advanced considerably. Given these advances, our objective was to model suitable habitat for the long-footed potoroo, and use this updated SDM to guide camera surveys aimed at locating extant populations in NSW. Further, in the absence of detailed data on abundance or other proxy measures of long-footed potoroo habitat quality in NSW, this study proposed to use field surveys to ground-truth the SDM predictions. Such information is critical to assess the likelihood that populations of this marsupial remain extant in NSW and, if so, aid the recovery of the species.

METHODS

Species Distribution Modelling - Maxent

To establish the long-footed potoroo's current potential distribution in NSW, species distribution modelling was undertaken with Maxent (Version 3.3.3k) (Phillips *et al.* 2006; Phillips & Dudík 2008). This type of SDM does not require absence data and is well-recognised as having high predictive performance (Elith *et al.* 2006). The program requires up to three key data inputs: i) species occurrence data; ii) data describing environmental predictor variables across the study area; and iii) "background" points representing a sample of the available environment across the study area (optionally adjusted for sampling bias) (Syfert *et al.* 2013). To investigate the impact of different covariate combinations on model predictions, several model iterations were run using Maxent's default settings, with two exceptions relating to background points and feature selection (outlined below). The Maxent models in this paper were calibrated at 250 × 250m resolution, thought to be appropriate for capturing spatial environmental heterogeneity relevant to potoroo habitat, and permitting the use of a range of available climate, vegetation and topographic data.

Occurrence Data

Species occurrence records were obtained from the Atlas of Living Australia (ALA) database (<http://www.ala.org.au>). The 531 occurrence records were examined to identify definitive records of the species (i.e. locations where the animals were live-trapped, camera-trapped, detected by hair-tubes; and/or had reliable expert observers). Spatially invalid or duplicate records, and those that were poorly georeferenced (e.g. coordinate uncertainty >1000m), were deleted. As the potoroo was identified as a distinct species in

133 1980, records with dates stated as ‘first of the century’ (i.e.1/1/1900) or before 1980 were
134 included only if they were sourced from a “preserved specimen”. Following the data
135 cleaning process, there were 341 occurrence records remaining; 34 from NSW and 307
136 from Victoria. The occurrence records were projected to the Australian Albers Equal Area
137 (EPSG:3577) coordinate system and reduced to one record per grid cell (250m resolution)
138 in the R statistical computing environment (v3.1.1) (R Development Core Team, 2014),
139 leaving a total of 272 presence points for use in the model.

140 *Environmental Variables*

141 We used climate data for the period 1990–2009 that was generated as part of the NSW
142 and ACT Regional Climate Modelling (NARClIM) project (Evans *et al.* 2014). These data
143 represent a set of 35 bioclimatic variables, developed at a spatial resolution of 9 arc-
144 seconds (Hutchinson & Xu 2015; Appendix S1). Using a cubic spline, we reprojected the
145 data to EPSG:3577 at a resolution of 250 × 250m. Slope and aspect (both measured in
146 degrees) were calculated using the gdaldem function implemented in the gdalUtils R
147 package (Greenberg & Mattiuzzi, 2015). Aspect was decomposed to two variables
148 expressing the north-south (northness; cosine of aspect) and east-west (eastness; sine of
149 aspect) components, since these better represent insolation. National Vegetation
150 Information System (NVIS) vegetation categories were generated from NVIS Major
151 Vegetation Subgroups data (n= 38 categories) (Version 4.1) (Department of Sustainability
152 Environment Water Population and Communities, 2015) originally obtained at 100 × 100m
153 resolution. We resampled this to 250 × 250m, assigning the most common cell value to the
154 250m cell. This resulted in 39 environmental variables.

155 Variables incorporated into SDMs should be ecologically relevant, and while correlations
156 should be minimised, Maxent’s predictions are considered robust to correlated variables
157 (Elith *et al.* 2011; Guisan & Zimmermann 2000). We developed competing models using
158 different sets of environmental variables. The first model incorporated all 35 BIOCLIM
159 covariates only, consistent with a previous SDM for the species (Claridge 2002). Four
160 alternative subsets of the 39 variables were explored, informed by ecological relevance,
161 expert feedback, variable contribution, and variable correlation. All models produced high
162 AUC scores (> 0.9). The final ‘pre-survey’ model was selected based on visual inspection
163 of the resulting map and guidance from potoroo experts. This model included the following
164 seven variables: maximum temperature of the warmest week, precipitation of the driest
165 week, highest weekly radiation, lowest weekly radiation, lowest weekly moisture index,
166 mean moisture index of wettest quarter, and mean moisture index of driest quarter. These

variables were selected due to their influence on the species' primary limiting factor, the availability of fungi. Hotter, drier conditions will negatively affect soil and vegetation characteristics and limit the presence, diversity and abundance of associated hypogaeal fungi (Claridge *et al.* 2000). Two variables, lowest weekly moisture index (BIOCLIM 30) and mean moisture index of the wettest quarter (BIOCLIM 33) were highly correlated (Pearson's $r > 0.8$) (Appendix S6), however, the model was regarded by experts to be the most reasonable representation of the long-footed potoroo's likely distribution. The models were fitted with each set of variables using five-fold cross validation to define training and test data sets and to enable evaluation of model performance using the Area Under the Receiver Operating Characteristic curve (AUC). Maxent was permitted to generate linear, quadratic, and product features (transformations of the provided predictor variables). A multivariate environmental similarity surface (i.e., MESS maps; Elith *et al.* 2010) was generated (Appendix S2), indicating areas that involved model extrapolation to environmental conditions beyond those represented in the model-fitting data.

Background Points

By default, Maxent randomly samples 10,000 points from across the study area (the "background") and compares the environmental characteristics at these points to the characteristics at occurrence points. This approach assumes that the occurrence records are also a random sample from suitable locations across the landscape (Elith *et al.* 2011). However, sampling bias (e.g., towards settlements and accessible areas) is likely to be present in the occurrence data because of the *ad hoc* nature of many of these collections. Accounting for sampling bias is critical to the accuracy of SDMs generated from presence-only datasets, and failure to correct for it can result in predictions that reflect not just the distribution of suitable habitat but also of sampling effort (Phillips *et al.* 2009; Syfert *et al.* 2013; VanDerWal *et al.* 2009). Hence, to reduce sampling bias, we followed the approach outlined by Elith *et al.* (2011) by randomly selecting ~10,000 background records from all mammal records in the ALA that were recorded from the four bioregions (Interim Bioregionalisation of Australia, Thackway & Cresswell, 1995) within which the long-footed potoroo occurs (Australian Alps, South East Coastal Plain, South East Corner, South Eastern Highlands). Sampling bias present in observations of these mammals will not perfectly reflect that for the long-footed potoroo, as there have been some strategic, planned surveys for this species. However, we expected that the bias would be captured more effectively than if Maxent's default, random background was used.

201 **Long-footed potoroo Field Survey**

202 *Study Location*

203 The study area was located in South-East Forests National Park (SEFNP), in south-
204 eastern New South Wales (NSW) (Figure 1; Appendix S3). NSW survey sites for the
205 present study were located on seven vegetation classes: South East Dry Sclerophyll
206 Forests, Southern Hinterland Dry Sclerophyll Forests, Southern Escarpment Wet
207 Sclerophyll Forests, South Coast Wet Sclerophyll, Southern Warm Temperate Rainforests,
208 Tableland Clay Grassy Woodlands, and Eastern Riverine Forests (Office of Environment
209 and Heritage, 2012) (Appendix S4). Elevation across sites ranged from 170 to 1,144m
210 a.s.l. The SEFNP is bounded predominantly by areas of State Forest and private
211 agricultural land-holdings.

212

213 *Site Selection*

214 Survey sites (i.e. 500m transects) in NSW were selected based on Maxent's model output.
215 To meet our dual objectives of species detection and ground truthing the model, sites were
216 stratified across the predicted habitat suitability (HS) gradient. Model output (i.e. HS
217 values) was reclassified into four climate suitability bands that were loosely based upon
218 the range of predicted HS values at locations where long-footed potoroos had been
219 detected previously:

- 220 a) Low (Unsuitable): 0–0.13 (i.e. below the “equal test sensitivity and specificity” binary
221 threshold of 0.13, which was based on the average of five cross-validation folds);
- 222 b) Low-Moderate: 0.13–0.61 (above “Low”, but below the 50th percentile HS value of
223 known occurrences);
- 224 c) Moderate: 0.61–0.89 (between the 50th and 100th percentile of known occurrences);
225 and
- 226 d) High: 0.89–1 (above HS values of known occurrences)

227

228 We overlaid the reclassified map of the study area with topographic layers (rivers,
229 contours, land-use types (SEFNP boundaries vs State Forest), and roads), and
230 haphazardly selected 58 survey sites that were located within 100m of the nearest access
231 track and were primarily within SEFNP boundaries (thereby ensuring accessibility). In
232 addition, as the long-footed potoroo's home range has been estimated to be between 14–
233 100ha (Green *et al.* 1998; DSE 2009), we ensured that sites were independent by
234 separating them by approximately 1km or more. This distance is consistent with the recent

235 long-footed potoroo survey carried out in Victoria (pers. comm. Andy Murray, DELWP, 1
236 December 2016).

237 Note that in NSW, there were no grid cells in the study area that were classified as having
238 'High' HS. Rather, areas with the highest HS values in NSW were in the 'Moderate' HS
239 band. From this 'Moderate' region, we identified 15 sites that met the above criteria. Of the
240 remaining sites, four were intentionally located close to potoroo occurrence records in
241 NSW (within ~500m) (n=3 situated in 'Low-Moderate' HS band; and n=1 in the 'Low' HS
242 band) and the rest were allocated approximately equally across the 'Low-Moderate' (n =
243 20) and 'Low' (n = 19) HS bands (Figure 1; see also Appendix S3 for detailed maps). Most
244 sites (49) were purposefully located in areas that had not been logged or exposed to fire
245 for at least 25 years, giving sufficient time for forest succession to occur and resulting in
246 greater habitat complexity (Coops & Catling 2000).

247 *NSW Survey: Camera Trapping*

248 Due to the likely low population density and patchy distribution of the long-footed potoroo
249 in NSW, individuals may be difficult to detect using traditional survey methods, e.g. live
250 trapping and hair tubing. As such, camera trapping is likely more effective (Scroggie *et al.*
251 2011), with recent camera trapping in Victoria proving highly successful for detecting the
252 potoroo (pers. comm. Andy Murray, 1 December 2016, and Marc Perri, Department
253 Environment Land Water & Planning (DELWP), 6 December 2016).

254 We performed camera surveys in NSW during six field trips between April 2016 to May
255 2017. Up to 10 sites were trapped on each trip, and at each site 6 - 8 baited camera
256 stations were deployed along the 500m transect, 100m apart. Baits, containing oats and
257 peanut butter or peanut butter only, were suspended 20–30cm above ground (Claridge *et al.*
258 2016; Paull *et al.* 2011). Following Claridge *et al.* (2010) and Taylor *et al.* (2014)
259 cameras were mounted on a tree (40–80cm above the ground) at a distance of 1.5–2m
260 from the bait station and left in-situ for up to 63 days (minimum 52 days; median of 59)
261 (Appendix S5). This extended deployment time, more than double that recommended for
262 95% detection of the species (Scroggie *et al.* 2011), was considered necessary to
263 maximise detection probability.

264 Two types of passive infrared (PIR) cameras (four Reconyx Hyperfire HC600 (hereafter
265 "Reconyx") and up to four Scoutguard DTC-530V (hereafter "Scoutguard")) were placed
266 along each transect in a consistent order (i.e. two sites containing both cameras, two sites
267 with Reconyx only and two sites with Scoutguard only; however, when only six cameras
268 per site were available it was four sites with Reconyx only and two with Scoutguard only).

269 The motion detection trigger settings were: i) Reconyx: “High” sensitivity, 5 images per
270 trigger event, 1 second delay between triggers and 1 minute quiet period; ii) Scoutguard:
271 “High” sensitivity, 3 images per trigger, 5M resolution (highest resolution setting) and 1
272 minute quiet period. Camera images were reviewed by MWD and Office of Environment
273 and Heritage (OEH) experts. Images of potoroos were forwarded to two additional potoroo
274 experts for species identification and confirmation.

275

276 **Data Analysis**

277 *Model validation with an independent dataset*

278 Modelling species’ distributions is an iterative process and models should be assessed
279 and recalibrated as new information becomes available. After completion of fieldwork,
280 which was guided by the “pre-survey” SDM, three additional long-footed potoroo presence
281 and absence datasets became available. These were: i) absence data generated from the
282 current NSW field survey (n = 58); ii) presence data from Victorian camera trap surveys
283 conducted during 2012–2016 (n = 91), but not incorporated in the Victorian Biodiversity
284 Atlas at the time of Maxent modelling (data courtesy of Marc Perri, 6 December 2016); and
285 iii) absence data from Victorian camera trap surveys conducted in 2012 (n = 128) (data
286 courtesy of Jenny Nelson, DELWP, 5 July 2017, refer to Lumsden *et al.* (2013) for further
287 details on survey methods). Hence, these records constitute a dataset independent of that
288 used in the original modelling.

289 To assess the predictive performance of the pre-survey SDM, we computed HS values for
290 presence and absence records in the independent dataset, and evaluated whether the
291 medians of these two groups differed, using a Kruskal-Wallis H Test (Bennett 1993) in
292 Minitab® Statistical Software (Version 17) (Minitab Inc, 2014).

293

294 *Updated post-survey Maxent models*

295 New observations may help to refine estimates of a species’ realised niche, or aid removal
296 of bias (Guisan *et al.* 2006). The nature of available data at the time of initial modelling
297 meant that the NSW field survey was informed by presence-only modelling techniques.
298 Hence, an updated ‘post-survey’ Maxent model was fitted that incorporated an additional
299 54 long-footed potoroo presence records from Victoria, spanning the period 2012–2016,
300 that were not previously included, giving a total of 395 presence records. The same
301 Maxent settings, background locations, and pre-survey model covariates were applied.
302 The post-survey model output was then contrasted against the initial model using the

303 Raster Calculator tool in the ESRI ArcGIS software, ArcMap 10.5
304 (<http://desktop.arcgis.com/en/arcmap/>), which was used to compute a difference map
305 expressing the difference in HS values projected by the two models.

306 **RESULTS**

307

308 **Pre-Survey: Maxent Species Distribution Model**

309 The pre-survey Maxent model had an average cross-validated test AUC value of 0.941
310 (SD = 0.011), indicating that the modelled outcomes could be considered a potentially
311 useful prediction of habitat suitability (Phillips & Dudík 2008). The most important variables
312 were mean moisture index of the highest quarter (29.7%), maximum temperature of
313 warmest week (24%) and mean moisture index of lowest quarter (19.9%) (Appendix S6). It
314 is noted, however, that while mean moisture index of the lowest quarter and lowest weekly
315 moisture index each provided unique contributions to the model, they were highly
316 correlated (Appendix S6), and thus the importance of the latter may be underestimated.
317 Covariate response curves indicated that the highest predicted HS values are in areas
318 with higher moisture (Appendix S6).

319 The model projected a large, contiguous area in Victoria to have the highest HS values,
320 consistent with the locations of known populations (Figure 2). In comparison, the few
321 areas in south-eastern NSW projected to have 'Moderate' HS are relatively small and
322 fragmented (Figure 2). This finding is similar to the historical BIOCLIM output, which
323 identified a large area of suitable habitat in East Gippsland, Victoria, and smaller patches
324 in NSW (Claridge 2002).

325 Of the 34 potoroo records in NSW, all are located in the 'Low-Moderate' HS band; with
326 many records located on flatter areas. As such, a number of 'Moderate' HS patches in
327 NSW (e.g. around Candelo Creek, Back Creek, Basin Creek, and Reedy Creek) do not
328 contain any known occurrences, and these may provide promising candidate locations for
329 survey work, though some sites are relatively inaccessible (i.e. at higher elevations,
330 steeper slopes or along the sides of ridgelines). Areas predicted to have 'Moderate' HS
331 values occur within the SEFNP as well as State Forest, the latter of which is actively
332 logged and hence may be too disturbed to support potoroos.

333

334 Camera Survey

335 During this study, a total of 215,759 images (including false triggers) capturing 43 species
336 from 58 transect sites (or 431 individual camera sites) were recorded from 25,120 camera
337 trap nights. Incorrect camera settings (e.g. time lapse / video) on four cameras generated
338 a large number of images (102,412), of which only night images were reviewed in detail.
339 Images of potoroos were examined by experts (A. Claridge, A. Murray), who confirmed
340 they were of the long-nosed potoroo (*Potorous tridactylus*).

341 Fifteen native mammal species, 22 bird species and one reptile species were detected.
342 Seven introduced mammal species were also detected. Of the mammals identified, the
343 long-nosed potoroo and southern brown bandicoot (*Isodon obesulus*) are listed as
344 'Vulnerable' and 'Endangered', respectively, under the *Environment Protection and*
345 *Biodiversity Conservation Act 1999*, and considered at risk of fox and cat predation. Of
346 concern for native small- to medium-sized mammals is the dominance of foxes (*Vulpes*
347 *vulpes*) and feral cats (*Felis catus*), detected at 28% and 43% of survey sites, respectively.
348 Another potential predator, dingoes (*Canis lupis dingo*), were detected at 28% of sites.
349 The prevalence of these predator species across survey locations is relatively high (71%
350 of sites), particularly considering that meat lures were not used, and sites were not
351 situated on roads or tracks. A full list of the species detected, the total number of sites
352 occupied and a breakdown across the Maxent model suitability bands is given in Appendix
353 S7.

354 Despite our efforts, no long-footed potoroos were detected, hence survey sites in NSW
355 were deemed 'absences'.

356

357 SDM Ground Validation

358 Using the independent datasets outlined above (see "Model Validation"), a comparison of
359 HS values at presence ($n = 91$) and absence ($n = 186$) locations highlighted variability
360 within these two groups as well as some overlap between them (Appendix S8).
361 Furthermore, 72% of long-footed potoroo absences are in areas that may be considered
362 "suitable" when the cross-validated mean 'equal test sensitivity and specificity' binary
363 threshold is applied. Overall, however, the Kruskal-Wallis test of mean ranks revealed that
364 there is a statistically significant difference between HS values at presence and absence
365 locations ($H = 58.66$, $df = 1$, $p < 0.01$). This result suggests that the pre-survey Maxent
366 model used to guide the field survey tends to perform well.

367

368 *Post-survey Maxent*

369 The post-survey model generated an average cross-validated AUC of 0.944 (SD = 0.007)
370 (slightly higher than the pre-survey model), suggesting that the model is a useful classifier
371 of habitat suitability (Phillips & Dudík 2008). Maximum temperature of the warmest week
372 (27.4%), mean moisture index of the lowest quarter (22.2%), and mean moisture index of
373 the highest quarter (19.9%) were found to contribute most to the fit of the model.

374 Comparison of the pre- and post-survey models revealed several regions where
375 projections of habitat suitability differed (Figure 3). In NSW, there are areas predicted to be
376 relatively more suitable than indicated by the pre-survey model. It is unlikely that this
377 would have given rise to significant changes to the selection of survey sites as, in general,
378 accessible areas with the highest HS values in NSW were targeted, and these areas
379 continue to have similar (i.e. 'Moderate') HS values in the updated model. Of interest,
380 however, is that the interior Genoa area, north of Sheep Station Creek, and the Nungatta
381 Plateau area (adjacent to Nungatta Station) are predicted to be relatively more suitable (as
382 indicated in Figure 3). These areas are rather remote and difficult to access, hence were
383 not targeted for our survey.

384 **DISCUSSION**

385

386 **The case of the missing potoroo**

387 Identifying where species occur underpins many conservation management decisions
388 (Guisan *et al.* 2013) and the use of species distribution models to guide field surveys has
389 been valuable for many species (Aizpurua *et al.* 2015; Guisan *et al.* 2006). However, no
390 long-footed potoroos were detected during our SDM-guided surveys in NSW. As such, the
391 distribution of this Critically Endangered species in NSW remains unclear and is founded
392 upon records collected in the 1990s.

393 **Simply not there?**

394 We did not detect long-footed potoroos in any areas predicted to have relatively high
395 habitat suitability (HS) values in NSW, or from a wider range of areas that were considered
396 suitable when a binary threshold was applied to model output. Furthermore, the species
397 was not detected at sites close (< 1km) to where historical records were obtained.
398 Possible explanations for the species' absence include: unsuitable microhabitat,
399 fluctuations in population dynamics, impact of disturbance events (e.g. fire and logging)
400 and presence of introduced predators and competitors.

401 Microhabitat features are an important factor influencing the distribution of mycophagous
402 mammals, including long-nosed potoroos (Bennett 1993; Claridge & Barry 2000; Vernes
403 2003) and it is possible that the resolution of the SDM (i.e. 250 × 250m) did not capture
404 microhabitat characteristics. Generating predictive maps using SDMs requires covariate
405 datasets that span large spatial areas, which rarely exist for biotic and fine-scale abiotic
406 factors. We note, however, that a number of survey sites with 'Moderate' HS values
407 appeared visually to have appropriate microhabitat characteristics (e.g. Tantawangalo and
408 in pockets of temperate rainforest). In these locations, it is possible that the potoroo is
409 locally extinct, or was simply never there, particularly as many of these sites were distant
410 from historical presence records.

411 Some sites in NSW may have suitable microhabitat but are unoccupied because the patch
412 is either too small or located too far from populated sites. Indeed, most areas predicted to
413 have highest suitability in NSW were small and patchy (Figure 3). For instance, the area in
414 Tantawangalo with relatively high HS values was ~950ha in size and located ~10km from
415 the next patch of suitable habitat at Wog Way, Coolungubra (~780ha).

416 Habitat fragmentation is likely to exacerbate poor connectivity of climatically suitable
417 areas. There has been significant land use change in the study area over time, with large
418 areas of SEFNP bounded by pine plantations and pastoral lands. Fragmentation disrupts
419 ecological processes and restricts the movement of organisms, thereby isolating
420 subpopulations and increasing extinction risk (Gilbert-Norton *et al.* 2010; Worboys &
421 Pulsford 2011).

422 Disturbance events such as logging and fire may also negatively impact the potoroo via
423 direct mortality, reduced vegetation cover and food availability, increased exposure to
424 predators, and disrupted social structure (DSE 2009). In an attempt to limit the influence of
425 these factors on detectability, most survey sites were situated in locations that had not
426 experienced fire or logging for more than 25 years. However, it was frequently apparent
427 that logging had occurred in the past, and may have contributed to absence or non-
428 detection of the species. We also note that many occurrence records are located in
429 previously logged forests (including the long-term Bellbird study site). This suggests that
430 regrowth forests are utilised by the potoroo (DSE 2009), although it is also known that
431 potoroos inhabiting mature, multi-aged and old growth forest tend to forage for shorter
432 periods, have smaller home ranges and are more fecund (Green & Mitchell 1997; Green *et*
433 *al.* 1998).

434 Finally, the presence of feral pigs (*Sus scrofa*), another highly mycophagous species, is a
435 key threatening process for the long-footed potoroo as both species compete directly for
436 hypogeal fungi (NPWS 2002). The camera survey detected feral pigs at approximately
437 15% of sites. The long-footed potoroo is also at risk of predation by foxes and cats, which
438 were detected at nearly 50% of sites. These findings are of concern for the persistence of
439 the long-footed potoroo.

440

441 **A clever disappearing act?**

442 It is possible that the long-footed potoroo remained hidden, defying detection due to its
443 likely low population density in NSW. In the present study we tried to maximise detection
444 by using best practice survey methodologies: camera trapping, baited traps and extended
445 deployment times. Camera trapping has been widely used for species surveys and has
446 been more successful for detection of small- to medium-sized mammals, including the
447 long-footed potoroo (Claridge *et al.* 2010; Paull *et al.* 2012; Smith & Coulson 2012; Taylor
448 *et al.* 2014), than other methods (e.g. Elliot traps, cage traps and artificial traps)
449 (Welbourne *et al.* 2015). Recent camera surveys for the species in Victoria utilised
450 deployment times ranging between 21 days (Lumsden *et al.* 2013) and 35 days (pers.
451 comms. Andy Murray, 1 December 2016), successfully recording the species at 41 (out of
452 170) and 35 sites (out of 85), respectively.

453

454 ***Looking forward: ongoing model refinement***

455 The success of a field survey guided by an SDM hinges upon the quality of the underlying
456 SDM. Guisan *et al.* (2006) noted four elements that contribute to the usefulness of a
457 model: i) positional accuracy of species occurrence records; ii) inclusion of only
458 ecologically relevant predictors that are expected to have a physiological effect on the
459 species; iii) use of an appropriate model based on available data; and iv) generation of
460 background points from presence sites of other species when absence data are not
461 available. These elements were considered during the development of the Maxent model.

462 The choice of relevant predictors and appropriate resolution for data used in an SDM may
463 invoke a trade-off between using larger, accessible datasets and spatial accuracy in
464 describing a species-environment relationship (Le Lay *et al.* 2010). The Maxent model
465 used here incorporated ecologically relevant climate variables that operate over larger
466 scales. Independent model validation found that the pre-survey model could successfully

distinguish between presences and absences, although there was variability of HS values within each group (i.e. presence/absence).

It is also worth noting that the NSW occurrence records were situated in areas predicted by the pre-survey model to have 'Low-Moderate' HS values, with the 'High' HS value areas predicted only in Victoria. This suggests that the climatic conditions in Victoria, where the majority of current occurrence records are situated, were less frequently encountered in SE NSW where only smaller, patchy areas of relatively higher suitability were predicted. The small number of occurrence records located in NSW makes it difficult to draw a conclusion about the veracity or validity of the model.

However, future models could potentially be refined by incorporating other relevant environmental predictors. For example, soil characteristics are likely to play an important role in predicting the presence of the potoroo by influencing vegetation type and soil moisture, both of which can impact fungal diversity and abundance. Structural attributes of the vegetation are also likely to be important. For instance, attributes of eucalypts (diameter at breast height and upper canopy cover) relate to availability of hosts for hypogeous fungi (Claridge *et al.* 2000), while understorey cover and density are important for providing shelter, nesting sites and protection from predators (Scotts & Seebeck 1989; DSE 2009). As previously noted, connectivity and patch size could also be important predictors. Time and resource constraints limited our ability to include these variables in the pre-survey model, but consideration of these variables for inclusion in a future model would be highly worthwhile.

An alternate modelling approach, applied for another mycophagous species, the northern bettong (*Bettongia tropica*), was outlined by Bateman *et al.* (2012) who generated a resource SDM and a competitor SDM. The predicted values from these models were incorporated into an SDM of the target species (i.e. climate + resource + competition variables), giving rise to models with stronger evaluation measures (AUC) than models utilising climate data alone (Bateman *et al.* 2012). Such an approach may be useful for the long-footed potoroo, whose presence is likely limited by fungal availability, competitors and predators.

Finally, models incorporating both presence and absence data have been found to outperform presence-only techniques (Webb *et al.* 2014). Given the additional presence and absence data from camera surveys in Victoria from 2012–2016, as well as 'absence' data generated from our surveys, it would be worthwhile investigating alternative modelling

500 techniques, e.g. regression based SDMs such as Generalised Linear Models (GLM) or
501 Generalised Additive Models (GAM).

502 The benefits of ongoing model refinement were highlighted by the post-survey Maxent
503 model. The inclusion of additional presence records from Victoria led to several areas
504 being identified as more suitable than previously predicted. These areas are relatively
505 isolated and inaccessible. Access to the Nungatta and Nalbaugh Plateaus via helicopter
506 was recently organised for OEH staff, and low-density camera surveys were undertaken.
507 This did not yield any new long-footed potoroo sightings (JB, unpublished data, November
508 2017). However, other nearby areas may be worth considering for future surveys. Prior to
509 conducting these surveys, the use of new data layers (e.g. vegetation structure estimated
510 by LiDAR) or technologies (e.g. drones) could be considered to identify suitable
511 microhabitat features that may improve the likelihood of the species being detected.

512 In conclusion, species distribution models provide a useful starting point for directing
513 limited resources toward field surveys for very rare and threatened species. The pre-
514 survey Maxent model presented in this paper predicted a distribution of habitat that
515 provided insights into a number of new survey locations for the long-footed potoroo in
516 NSW. Model validation using an independent presence/absence dataset supported the
517 predictive capabilities of the model. The field survey did not detect the species, although
518 there remain large areas of the SEFNP that were not surveyed, either due to time
519 constraints or limited accessibility. Areas closer to the coast (e.g. Nadgee Nature Reserve)
520 may also be worth surveying, particularly given recent findings of the species in coastal
521 habitats in Victoria. Model refinement that includes additional environmental factors, such
522 as soil type, biotic interactions, microhabitat features and connectivity, would be an
523 informative next step. Regardless, if the long-footed potoroo is still present in NSW, it is
524 likely to be extremely rare.

525

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