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Stable detection frequency of the threatened Christmas Island Boobook *Ninox natalis*, 2012–2022

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ABSTRACT
Both island species and raptors are at particularly high risk of extinction but few island raptor populations have been the subject of long-term monitoring. To determine trends in abundance in the Christmas Island Boobook, surveys were conducted annually from 2012–2017, in 2019 and in 2022. Across the survey period the population appears to have been either stable or to have increased slightly. Almost no part of the island lacked owls during the most recent survey. The detection rate averaged 1.56 (out of four surveys at a site); it was lowest in 2013 (1.22) and highest in 2022 (2.38). Detection was more likely on nights with low wind, at wetter sites and in closed vegetation, rather than in open or very low vegetation. In a separate analysis on the same data, the top-ranked dynamic occupancy-detection model found that occupancy increased with increasing elevation and vegetation height. No effect of a suspected threat, the presence of invasive yellow crazy ants *Anoplolepis gracilipes* at a site, could be detected. We recommend ongoing monitoring and research, potentially using automated recording devices and the tracking of individual owls to understand and refine the assumptions underpinning the interpretation of survey results.

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Forest owl; island population; stability; habitat suitability modelling; monitoring

Introduction

As top predators, raptors are functionally important species in many ecosystems (Newton 1979; Sergio *et al.* 2005) but many raptor species are threatened with extinction globally (Cruz *et al.* 2021). Island bird species are also particularly susceptible to extinction, making up 80–90% of all bird species extinctions (Szabo *et al.* 2012; Lees *et al.* 2022). In Australia, 38% of all bird extinctions since European colonisation have been of island taxa (Woinarski *et al.* 2024), well above the expected proportion of the country's bird species (Olah *et al.* 2024). The Christmas Island Boobook is a raptor confined to Christmas Island, an Australian external territory in the Indian Ocean with an area of 135 km^2. This small forest owl is strongly genetically differentiated from its nearest relatives (Norman *et al.* 1998; Gwee *et al.* 2017), nests in hollow rainforest trees and feeds primarily on insects, with small vertebrates augmenting its diet (Kent and Boles 1984; Phillips *et al.* 1991; Hill and Lill 1998b).

Christmas Island is thought to have been unoccupied by people until 1888, but since then has been subject to many conservation challenges. Since 1891, the island has been subject to mining for rock phosphate, with about 3,350 ha (25%) of the island cleared. From 1980, successive parts of the island were declared a National Park, which now covers 63% of the island. Of the 8,454 ha of national park, 93% is primary forest, while 7% has been mined and is subject to rehabilitation. A further 2,337 ha of primary rainforest occurs outside the national park and is protected by a moratorium on clearing introduced by the Australian Government in 1988. The island has also been affected by invasive species. In the last two decades, one reptile and one mammal species have become extinct, and two reptile species are extinct in the wild (Woinarski 2018; Emery *et al.* 2021) with invasive species strongly implicated. A particularly influential invasive species has been the yellow crazy ant which formed enormous

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colonies across much of the island from the early 1990s onwards, disrupting ecological systems (O'Dowd *et al.* 2003), and has been the subject of intensive control programs for over two decades (Boland *et al.* 2009).

Because of these losses, the general propensity for loss of island species, the number of potential threats in place, and the intensity of management of yellow crazy ants using poison baits, concern has periodically been expressed for the Christmas Island Boobook (e.g. Debus 2002; Low and Hamilton 2013). The species is currently listed as Vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999* and by the IUCN (BirdLife International 2022). Historically, van Tets (1975) suggested, with no evidence, that 10–100 pairs were breeding on the island and Stokes (1988) proposed there were 100 pairs. In contrast, with evidence from radio-tracking five individual owls, territory mapping of two 1 km^2 plateau forest blocks and call playback data from 22 sites across the island, Hill and Lill (1998a) concluded that the island supported 562 ± 105 boobook territories, excluding any living in the island's small urban area. James and McAllan (2014) considered that the best available estimate of population. However, Low and Hamilton (2013) concluded, based on a small-scale call playback study, that the population size in July–September 2011 was closer to the numbers in the earliest estimates of van Tets (1975) and Stokes (1988). In contrast to Hill and Lill (1998a), they suggested that owls were common around the settlement areas only. Morcombe (2016) subsequently undertook a larger-scale survey in July–September 2015 and concluded there were 342 mature individuals, or possibly only 240 if 30% of individuals were unpaired.

Nevertheless, two assessments of extinction risk, while still considering the species to be Vulnerable because of its small population size (250–1,000 mature individuals), both concluded that the population was stable (Garnett *et al.* 2011; Macgregor *et al.* 2021) with 'low' and 'medium' reliabilities, respectively. Macgregor *et al.*'s assessment was based on occupancy models applied to annual survey data up to 2017 (Director of National Parks, unpublished data).

Here, we extend that dataset to 2022 and report on trends in detection and habitat occupancy of the Christmas Island Boobook over 11 years. We applied generalised linear mixed models (GLMM) to estimate detection rates and dynamic occupancy detection models (DODM) to estimate trends in occupancy while accounting for imperfect detection.

Methods

Unlike most tropical raptors (Buechley *et al.* 2019), the Christmas Island Boobook has been surveyed repeatedly over the last three decades. Although there have been four different survey protocols (James and Retallick 2007; Low and Hamilton 2013; Morcombe 2016), each has been a variation on the methods employed by Hill and Lill (1998a). The methods used involved listening for boobook calls at multiple sites, up to five times each, for a fixed period of time, with call playback used by some but not all surveyors.

Data used in the current analysis were collected using the method applied in 2006 by James and Retallick (2007). However, data on boobooks from 2006 were not included in the current analysis because of some potential biases detected during analyses. The data analysed here were collected in surveys undertaken in 8 years over an 11-year period: annually from 2012–2017 inclusive, in 2019 and in 2022. No surveys were conducted in 2018, 2020 or 2021.

Surveys were undertaken at a series of fixed sites across the island. In the years 2012–2017, 124 sites were surveyed (Supplementary Figure S1). In 2019 and 2022, a further nine sites were surveyed (see Schulz 2019), making a total of 133 sites surveyed. Most sites were on vehicular tracks, some small and rarely used (James and Retallick 2007).

Owls call throughout the year (Hill and Lill 1998c) but all surveys took place from late May to mid-August, at the end of the wet season and in the first part of the dry season to minimise the chance of inclement weather (Supplementary Figure S2). Each site was surveyed four times in each survey year; visits to each site occurred on separate nights spread throughout the survey period. Observers remained stationary at a fixed point in the centre of each site while they listened for boobooks for 10 mins. All calls recognised as boobooks' and all sightings were recorded as indicating presence. No playback was used. Similar data were concurrently collected on the Christmas Island Flying-fox *Pteropus natalis* (Woinarski *et al.* 2012).

Although multiple observers were present during most surveys (number not recorded), one person was the primary observer (generally the most experienced person present). Only data collected by the primary observer were used in this analysis. Each primary observer was allocated a label, with observers who surveyed < 50 sites being grouped for the purposes of analysis. No attempt was made to test or standardise the detection capabilities of observers.

Fixed site data

For each survey site, the following information was collected (Supplementary Table S1):

Area surveyed: This was the area of land in hectares, excluding the sea. Any owl that called within 400 m was assumed to be audible under most survey conditions. However, this was not tested for, and the area within which owls were detected could be expected to vary with survey conditions (capabilities of the observers, wind, rain, strength of owl call, etc.). The area of land within a 400 m radius around the central point was adopted as a proxy for the habitat most likely to have been used by boobooks; this was a maximum of 50.3 ha, but smaller where the circle subtended the ocean (30/136 sites). This proxy was retained in the analysis as a covariate for all sites; even though one site was 61% ocean, owls were recorded in 50% of surveys there.

Elevation above sea level: Elevation of the central point of each site was extracted from a digital elevation map.

The Christmas Island Topographic Wetness Index: A Topographic Wetness Index (TWI), which provides a proxy for soil moisture, was derived in 2018 from a digital elevation model (Selwood *et al.* 2018). It was averaged across the surveyed area of each site.

Vegetation height: Vegetation was classified into eight height strata (0–5 m, 5–10 m, 10–15 m, 15–20 m, 20–25 m, 25–30 m, 30–35 m, 35–40 m) and the area of each category was estimated within the surveyed area of each site. The average was calculated from the sum of the products of the mid-point of each size class and the area of that size class divided by the land area surveyed.

Vegetation type: Vegetation on Christmas Island is categorised as being in one of eight types (Geoscience Australia 2014):

(i) Closed canopy evergreen forest;
(ii) Coastal fringe vegetation (herbland, shrubland);
(iii) Not vegetated (bare ground, coastal pinnacles/sand, infrastructure, mining, residential);
(iv) Perennial wetland forest;
(v) Regrowth;
(vi) Rehabilitation;
(vii) Semi-deciduous (scrub, forest); and
(viii) Weed dominated vegetation and pioneer regrowth.

The area of each vegetation type within each terrestrial surveyed area was calculated for each 5 m height category. To characterise vegetation, the dominant features were classified on two scales – *structure* and *origin*.

Vegetation structure was characterised as:

(i) Very low (<5 m, not vegetated);
(ii) Closed (closed canopy evergreen forest, perennial wetland forest, regrowth, rehabilitation, weedy regrowth or mixed weed and pioneer species); and
(iii) Open (coastal fringe shrubland, semi-deciduous scrub and forest and weed dominated vegetation and pioneer regrowth).

Vegetation origin was characterised as:

(i) Other (<5 m or not vegetated, as above);
(ii) Original (closed canopy evergreen forest, coastal fringe vegetation, perennial wetland forest, semi-deciduous scrub and forest); and
(iii) Novel (regrowth, rehabilitation, weed dominated vegetation and pioneer regrowth).

Sites were then assigned to one structure and one origin category based on the dominant vegetation in the surveyed area.

Variable site data

Ant colonies: The proportion of the surveyed area of each site affected by yellow crazy ants was assessed in 2012 and 2019 only. This was quantified as the proportion (%) of the surveyed area with high ant density (supercolonies, as defined by Abbott 2006), and the proportion affected by moderate ant density.

Climate: The antecedent rainfall in the 12 months preceding the date of each survey was obtained from the Bureau of Meteorology for the Christmas Island Aerodrome site.

Survey specific data

Time: The start time varied from 17:57 h to 01:03 h.

Weather: Wind speed (low, 0 and 1 on Beaufort scale; medium, Beaufort 2 or 3; high, Beaufort 4, 5 or 6) and rain were recorded for every survey. Nights with rain or high winds were avoided as much as possible, but some surveys were conducted in imperfect conditions.

Boobooks detected: Data were recorded on boobooks heard calling but specifics varied among years. In 2012, the time of the first call heard was recorded. From 2013, the number of boobooks calling at any time was recorded, with details obtained in up to four calling bouts each survey. From 2014, the distance from the observer was estimated and in 2017 and 2022 the compass bearing of any call was recorded. Distance and bearing were used to calculate the distance between any pair of boobook detections:

$$\text{distance(m)} = \sqrt{\left((d_1 * \sin\theta_1 - d_2 * \sin\theta_2)^2 + (d_1 * \cos\theta_1 - d_2 * \cos\theta_2)^2\right)}$$

where d and θ are the distance (m) and direction (rad) of each detection.

Detection within 50 m of another call during the 10-min period was mapped to assess whether it was likely to be the same boobook. Although a boobook flying at only 20 km/hr could theoretically fly across the entire surveyed area in under 3 min, boobooks are territorial (Hill and Lill 1998b). Boobooks distant from the observer calling several minutes apart were assumed to be the same boobook if locations were estimated to be <50 m apart. Boobooks close to the observer (<100 m) with calls <2 min apart were considered to be different boobooks if >20 m apart.

For each of the fixed and variable site statistics, and for the survey-specific data, relationships were explored with the frequency with which owls were detected and the maximum number of owls detected at a site on a night.

The presence and relative abundance of owls during site visits were modelled using a GLMM approach in Genstat (VSN International Ltd. 2024). If available variables were correlated ($r > 0.7$), we selected just one of each pair of correlated variables for formal analysis. Specifically, we used TWI instead of vegetation height (because it is a more accurate measure estimated consistently across the whole island); and we used vegetation structure instead of vegetation origin. We omitted elevation as it was correlated with vegetation structure. Information on the observer was difficult to fit in the model (and therefore omitted) because many observers only recorded data in one or two years.

Owl presence (yes/no) during each survey was used as the response variable in a model with a binomial error distribution, and with site specified as the random term. Initially, we fitted only those fixed effects that were available from every year (i.e. year, Julian date (and its interaction with year), area surveyed, TWI, vegetation structure, antecedent rainfall, time and wind). We then tested additional terms that were available only in some years (% of dense ants, % of moderate ants). The influence of fixed effects was tested using Wald statistics.

Owl abundance (the maximum number of owls recorded in a survey) was used as the response variable in a model with a Poisson error distribution, and with site again specified as the random term. This model had a more limited time series than the model for presence, as the number of owls calling was not recorded in 2012. The influence of fixed effects (the same as those used in the model of presence) was again tested using Wald statistics.

Dynamic occupancy-detection modelling (MacKenzie *et al.* 2003) was used to predict the relationship between occupancy, elevation and vegetation height, respectively, how presence and absence varied with year and detection probability for each wind and rain category in each year. These models were fitted in the 'unmarked' package (Fiske & Chandler, 2011) in R. A total of 24 separate models was fitted, each with different combinations of occupancy and detection variables. Only models with a ΔAIC <2 were considered in the results. We then modelled the predicted distribution of owls over space and time, running 1000 simulations using the probabilistic estimates of initial occupancy, colonisation (i.e. new occupancy of a site) and extinction (i.e. occupancy of a site ceasing) from the top set of fitted models for the entire study period (2012–2022).

Details on model structures and input parameters are provided in the Supplementary Material 1.

Results

A total of 4,040 surveys were conducted over the survey period and owls were detected in 1,572 (38.9%) of these (Supplementary Figure S3). Owls were detected at least once in all 133 sites over the 11-year survey period, but never at every site in a single year. Owls were recorded at 77% of sites in 2012, 69% in 2013, 84% in 2014, 61% in 2015, 74% in 2016 and 2017, 71% in 2019, and 94% in 2022 (all but seven of the 133 sites surveyed).

Owls were more likely to be detected in sites dominated by closed vegetation than in those with mostly very low or open vegetation (Figure 1(a)). This was also true of the maximum number of owls per survey, although that was highly variable (Figure 2(b)).

There was no relationship between the percentage of survey visits to a site during which owls were detected or the average maximum number of owls detected at a site and the site's elevation above sea level (Figure 1c,d), or Topographic Wetness Index (Figure 1e, f). Similarly, the origin of the vegetation was immaterial to either the

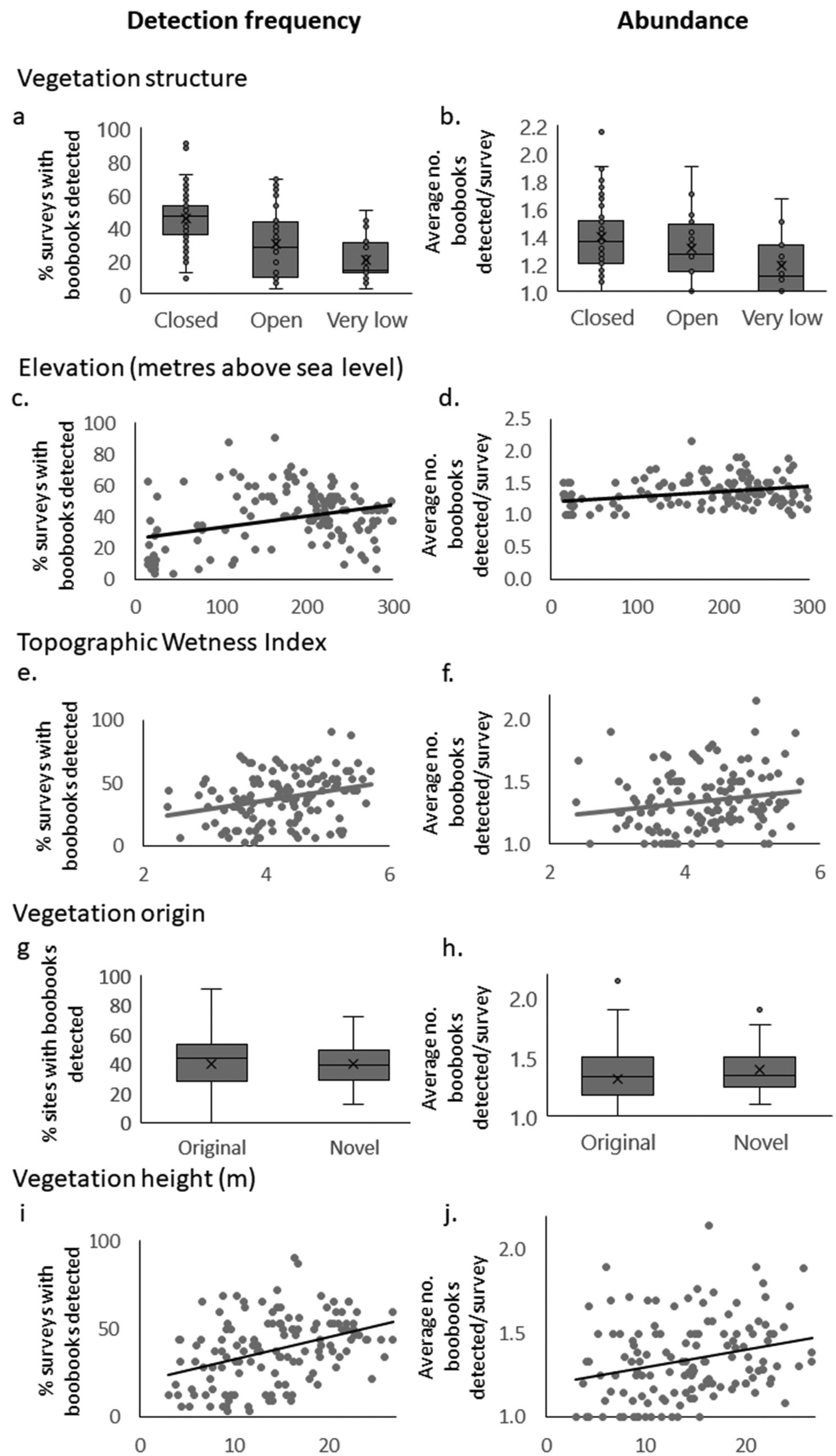

Figure 1. Overall surveys from 2006–2019, the relationship between the percentage of surveys at a site in which Christmas Island Boobooks were detected (left column) and the average maximum number of Christmas Island Boobooks detected during a survey (right column) and: (a and b) vegetation structure; (c and d) elevation; (e and f) Topographic Wetness Index;) g and h) vegetation origin, (i and j) vegetation height. For vegetation height, sites dominated by low vegetation or which had been cleared were excluded.

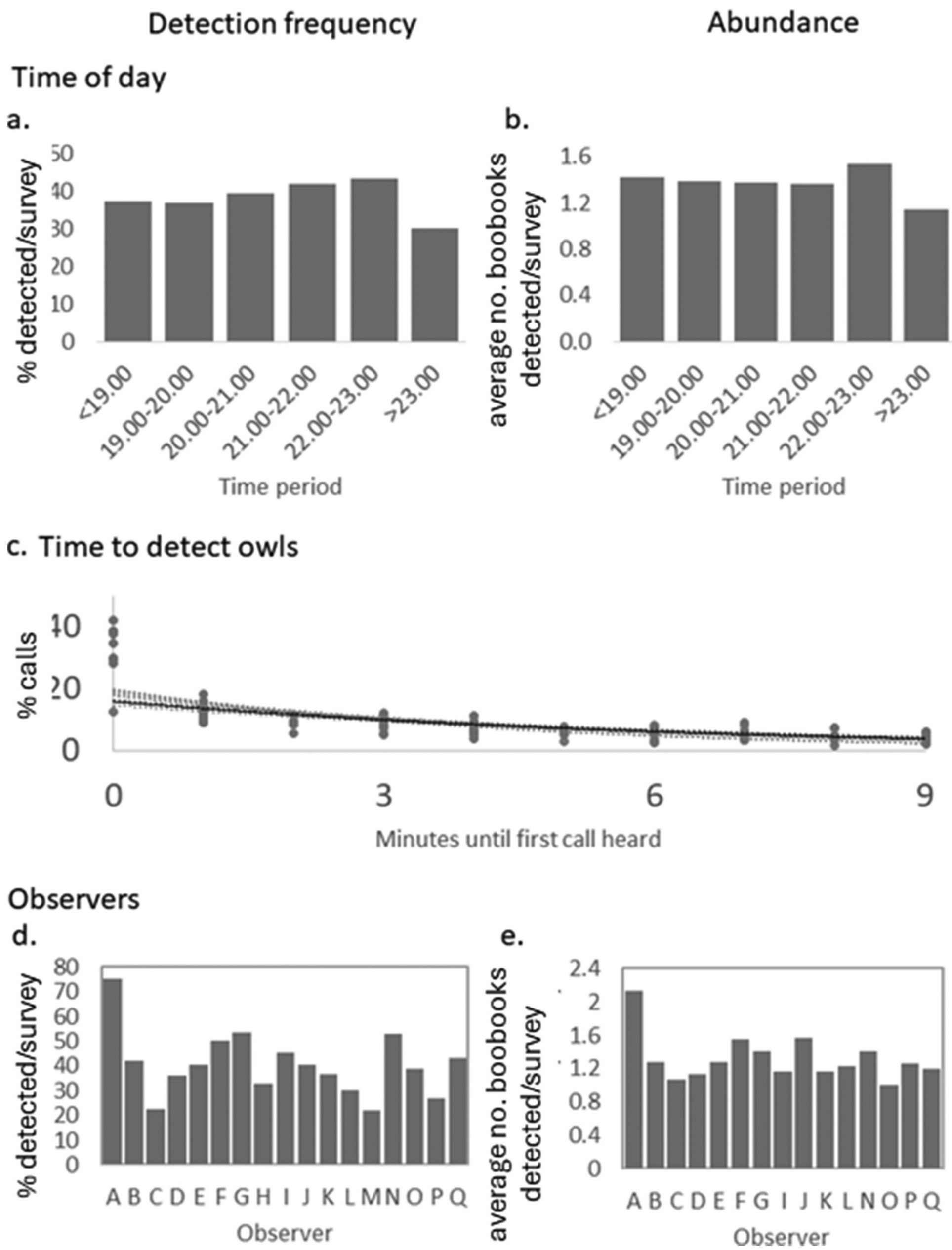

Figure 2. The relationship between the percentage of surveys at a site in which Christmas Island Boobooks were detected (left column) and the average maximum number of boobooks detected during a survey (right column) and (a and b) time of day; (c) the frequency of first detections after the 10-min survey period began (dotted lines represent detections in each year, thick line represents detections across all years and differences among observers in (d) the proportion of sites at which they detected boobooks and (e) the maximum number of boobooks they detected.

detection probability of owls or the average maximum number detected during a survey once the sites with low or no vegetation (Figure 1g, h) or the vegetation height (Figure 1i,j) were excluded.

Owl detections were not related to whether rain was recorded during the survey ($\chi^2_1 = 0.00$, $p = 0.95$), the time of the survey ($\chi^2_1 = 0.06$, $p = 0.95$) nor the accumulated rainfall in the months leading up to the survey season ($\chi^2_1 = 0.33$, $p = 0.56$). Owl detections were also not related to the proportion of area surrounding the site affected by moderate ($\chi^2_1 = 0.01$, $p = 0.93$) or high densities of crazy ants ($\chi^2_1 = 0.01$, $p = 0.93$), noting that including these terms in the model reduced the dataset considerably as the information was available only for three of the years.

Of the 1,671 detections of owls at a site, 1,643 were by call and 28 birds (1.7%) were seen before they called. There was some suggestion that surveys after 23:00 were less likely to detect owls (Figure 2(a)) but the effect was not significant ($\chi^2_1 = 0.186$, $p > 0.05$). On those occasions when owls were detected after 23:00, there is also a suggestion in the data that fewer were detected than earlier in the same evening (Figure 2(b)). Owls were usually detected quickly; 35% of all detections occurred within the first minute of a survey, presumably because an owl was already calling at that time, and 73% within 5 min (Figure 2(c)). Because detection probabilities tailed off gradually, there is a small likelihood that owls were still present but not detected. Of 39 people who were primary observers over the eight survey years, 16 surveyed > 50 sites, and six of those undertook surveys over multiple years. Although there was a 3.5-fold difference in the percentage of detections per person between the highest and lowest overall, with a factor of 6.5 within a year, the detection rate varied between 8% and 67% for an individual observer over multiple years, a factor of 8.5 (Figure 2d). The average number of owls heard per observer varied less (Figure 2(e)).

Wind had a profound effect on detectability. When surveys were made under conditions with little wind owls were detected on 48.0% of surveys, compared to 33.9% under moderate conditions and 21.1% when very windy. However, if owls were detected, the maximum number varied little (low wind 1.46, moderate 1.36, high 1.17 owls/detection). Detections were not related to whether rain was recorded during the survey ($\chi^2_1 < 0.01$, $p = 0.95$).

Detection

The probability that owls would be detected on a site visit was lower in 2015 than in 2014, but from 2015 to 2022 detections steadily increased ($\chi^2_7 = 106.3$, $p < 0.001$; Supplementary Figure S4a). Owl detections varied with Julian date and this relationship varied with year: detection probability tended to decrease with Julian date during 2012–2015 inclusive but increased with time from 2016 on ($\chi^2_7 = 53.1$, $p < 0.001$; Supplementary Figure S4b). Neither the timing of surveys nor the rainfall patterns shifted over time in linked ways. The change in detection patterns also hinge pre and post 2015.

As expected, owls were more likely to be detected when the survey area was larger (i.e. less ocean within the site radius) ($\chi^2_1 = 78.9$, $p < 0.001$) and when the wind speed was low ($\chi^2_2 = 127.5$, $p < 0.001$). Owls were also more likely to be detected at sites with high topographical wetness indices ($\chi^2_1 = 7.53$, $p = 0.006$). Owls were marginally more likely to be detected in closed vegetation than open and very open vegetation types ($\chi^2_2 = 4.46$, $p = 0.10$), noting that this term is somewhat correlated with the topographical wetness index.

Abundance

The number of owls heard calling was greater at sites with larger surveyed areas ($\chi^2_1 = 127.6$, $p < 0.001$), higher TWI values ($\chi^1_2 = 16.2$, $p < 0.001$), and when the wind was low ($\chi^{22} = 106.2$, $p < 0.001$; Supplementary Figure S5). Owl abundance varied strongly among years (highest in 2019 and 2022) ($\chi^2_6 = 316$, $p < 0.001$). However, the Year term also interacted with Julian date, whereby the number of owls declined with Julian date in later years (2017 to 2022) but not so in earlier years (2013–2016) ($\chi^2_6 = 38.8$, $p < 0.001$).

Owl abundance was not related to vegetation structure ($\chi^2_2 = 0.57$, $p = 0.56$), whether it rained during the site visit ($\chi^2_1 = 0.34$, $p = 0.56$) or the time of the survey ($\chi^2_1 = 0.87$, $p = 0.35$). Owl detections were not related to the proportion of the area surrounding the site affected by moderate crazy ant density ($\chi^2_1 = 0.08$, $p = 0.78$) or high crazy ant density ($\chi^2_1 = 0.00$, $p = 0.97$), noting that including these terms in the model reduced the dataset considerably.

Model fitting and prediction

The results of the dynamic occupancy-detection modelling were consistent with the models of individual factors, although there was no single best model, with seven having a ΔAIC <2 (Supplementary Table S2). The top ranked model by AIC included an effect of elevation and vegetation height on occupancy, of year on extinction and colonisation, and of wind and year on detectability. Occupancy was found to increase with increasing elevation and vegetation height. The covariates slope, topographic wetness index and distance to cleared areas were also included in the occupancy component of some top-ranking models, although their effect on occupancy was weak.

Detectability was higher when wind was 'low' compared to the 'medium' and 'high' categories. Detectability also varied between years, possibly due to different observers. Time of day and day of year were also included in the detection component of some top-ranking models, but their effect was weak compared to wind and year.

Boobooks were predicted to be relatively widespread and common across the island over time, although occupancy was predicted to have been higher in 2022 than in earlier years (Supplementary Figure S6). Similarly, mean detection probability was predicted to have increased over the duration of monitoring.

Discussion

Our results suggest that the population of Christmas Island Boobooks may have been stable from 2012 until 2015, but increased thereafter and was at its highest at the time of the 2022 survey. This conclusion is reached with both analytical approaches, although the dynamic occupancy-detection modelling suggests that there was possibly a weak gradual decline in predicted occupancy from 2012 to 2019 but that this trend was reversed in the final year. The slight differences between the two approaches are because the GLMM analysis modelled the detection rate, which combines occupancy and detection probability into one variable, whereas the dynamic occupancy-detectability modelling explicitly separates the two processes. Regardless of the approach taken, there were certainly at least as many owls in 2022 as there were in 2012 and the capacity for further increase is probably small given the small number of sites at which no owls were detected in 2022.

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Currently, the survey technique appears able to detect interannual changes in detectability of about 10% based on annual errors with the higher occupancy in 2022 likely to reflect a real difference in the size of the owl population. However, this certainty is somewhat compromised by the changes in detectability over time which suggest that the capability of observers may also be influencing survey results. The frequent changes in observers from year to year, the infrequency of observers surveying in multiple years and inadequate knowledge of drivers of owl calling behaviour and detectability all contribute to this variability. The differences in the impact of Julian date found with the GLMM analysis suggest variability in the owl's calling behaviour but the drivers of such variability can only be speculated.

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Vegetation and elevation

Overall, vegetation was identified as the major influence on whether owls occupy a site. The Christmas Island Boobook primarily occurs in the closed forests of the type that covered most of Christmas Island historically. Detection frequencies were much lower in open forest types and very low vegetation, whether natural or cleared. However, owls occurred in regenerating forest types where the canopy had closed. Although there is no information on whether owls breed successfully in such habitats (which probably have few if any hollow-bearing trees for nesting), they appear able to support owls at a density similar to that of closed forest. Some birds present may be occupying territories but lacking a mate, but the survey technique was not designed to distinguish single birds from pairs.

Although elevation was omitted from the final GLMM models because it was always correlated with vegetation structure, it was significant in DODM models, with TWI and slope being less influential.

Wind and rain

Owls were more difficult to hear, or called less, in windy weather. Rain also made it hard to hear owls but surveys avoided rain when possible so there was no statistical impact in any analysis. Even when rain was recorded, it usually started after the survey had begun, allowing some rain-free listening time.

Yellow crazy ants

No effect of yellow crazy ant presence was detected on either owl numbers or density in the three years with data. Thus, the results do not support speculations (Debus 2002; Low and Hamilton 2013; Morcombe 2016) that either the ants or the efforts to control them have reduced the owl population. There were several differences in survey techniques that could explain the lower detection rates of these other studies, but they are speculative without testing the approaches simultaneously.

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Given the detection of owls at least once at every site during the 11 year period, and their detection at 94% of sites in the 2022 survey, there is a reasonable chance that all habitat on the island is occupied. However, the actual number of owls on the island remains unresolved. Morcombe (2016), using detection data alone, suggested the number is likely to be lower than that estimated by Hill and Lill (1998b). Resolving that question would require a range of independent methods to estimate density accurately (e.g. radio tracking, territory mapping, nest searches and roost searches as well as census data), while taking other complicating factors into account (see Supplementary Information for further details).

Refinement of the current survey method

Given that 80% of owl detections occurred within the first 5 min of each survey, the current 10 minsurvey time appears adequate and could potentially be reduced by halving it to 5 minwith a correction applied to allow comparison with the existing 10 min data set.

Weather effects, which appear likely to have the strongest influence on detection, are already minimised by avoiding surveying on nights with rain or strong winds. Further understanding of the variability in boobook detectability could potentially be obtained by calibrating the capacity of individual observers to detect owls under standardised conditions and to understand the effects of habitat structure on detectability over different distances. With high turnover in observers between years, disentangling the effects on audible detection due to variabilities in observers, boobook behaviour, habitat structure and weather conditions would require substantially greater survey effort, the costs of which may exceed the benefits.

Possible alternative survey methods

Given that more than 98% of the 1,671 detections were initially by call, automated audio-recording devices have great potential for complementing or perhaps replacing existing surveys by people. Such devices could be used to determine patterns of calling at multiple sites so that survey methods might optimise detections. They might also provide a more accurate estimate of the proportion of owls that were present but missed. Audio recordings might also inform the timing of surveys to coincide with peaks in calling behaviour. For example, most of our surveys were conducted between 19:00 h and 21:00 h but Brighten (2015) found that, in temperate New Zealand, *Ninox novaeseelandiae* were more likely to call during the middle of the night and shortly before dawn. However, if audio devices were ever to be used to replace rather than complement surveys by people, careful calibration would be required to allow comparison with existing data.

Another option is the use of call-playback, which may increase the likelihood of vocalisation and thus detection. Even more careful calibration would be required to allow comparison with existing data, especially as both the capacity of owls to hear the calls and their response behaviour are unknown and will vary with both external conditions and the hormonal state of the owls. Given the repetition rate of our surveys, individual owls may become habituated to playback, potentially leading to a reduction in calling behaviour and a bias in long-term trends.

Hill and Lill (1998c) noted that individual owls could be identified by their calls. Individual identification could greatly improve the power of analyses of trends, and potentially reduce the survey effort required, since statistical power would increase if individual owls were identified between surveys within and between years. It could also facilitate population estimates with a level of an accuracy not possible with current data. However, characterising the individual calls of hundreds of owls would also be challenging, requiring sophisticated pattern analysis.

Given that the current method of passive listening is providing good data, any benefits in using new over existing methods, notwithstanding differences between observers, would need careful evaluation.

Suitability of rehabilitated habitat

There is uncertainty about the extent to which Christmas Island Boobooks use restored vegetation, even though they occur there. More detailed research could aim to detect evidence of breeding and, if detected, where that breeding occurs. The rate of hollow formation warrants further research, because it may be faster in Christmas Island rainforest than the drier vegetation types in which most hollow formation processes have been studied (Boyle *et al.* 2008). Feasibly, artificial hollows could also be trialled to assess whether natural hollows are limiting and/or to augment habitat suitability for owls in rehabilitated vegetation.

Owl movement patterns

Tracking in a range of vegetation types could also be used to settle some of the other uncertainties around calling behaviour, habitat use, nesting localities, densities, interactions among the owls and population size. Tracking a sample of owls fitted with transmitters could also be used to assess their detection probability using the current survey method.

Conclusions

Many island species are declining, particularly where there have been multiple introductions of alien species and substantial modifications of the pre-settlement environment. Currently the Christmas Island Boobook does not appear to be among them. Although we could not be certain whether there had been any decline due to intense poisoning of yellow crazy ants, we found no evidence that this had any lasting effect, or that the ants themselves were affecting owl occupancy or abundance. Repeated surveys suggest that the owls were near carrying capacity in 2022, occurring in almost all sites surveyed. The current survey method appears to be robust and should be sufficient to detect declines in the future before catastrophic loss occurs. While there is uncertainty about the absolute size of the population, the effort of trying to incorporate estimation of population size into regular monitoring would need to be weighed against the benefits of doing so. Nevertheless, questions remain about the ecology and conservation requirements of the species that could usefully be answered to inform management of the island and to guide interventions should they ever be required.

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Data availability statement

All data are presented in the paper or supplementary materials.

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