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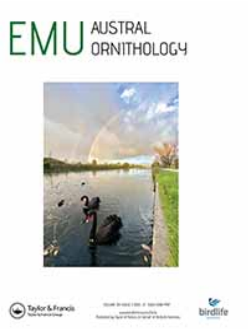

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The effectiveness of predator-proofing nest sites to support the breeding of an endangered parrot

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ABSTRACT
Invasive predators present a major threat to the conservation of native species. For birds, this often comes in the form of increased nest predation. Conservation managers have used numerous interventions to reduce this risk. However, their effectiveness varies depending on the specific technique used and the predators targeted. In this study, we tested the effectiveness of nest site modifications used to protect endangered Norfolk Island Green Parrot *Cyanoramphus cookii* nests from introduced mammalian predators. We compared the breeding outcomes and nest site characteristics of a sample of natural, unprotected nests with those of predator-proofed nests, and examined contemporary phenology and breeding parameters. We observed moderate, but variable, breeding seasonality, and significantly fewer nesting attempts in recent years. Nests had a median clutch size of five (range = 1–10) and a median brood size of three (range = 1–7). Nest success was 74.8% (157/210) for predator-proofed nesting attempts, and 40% (4/10) for unprotected nesting attempts. Predator-proofing had a small but significant effect on daily survival rate (estimated at 0.995 for predator-proofed nests and 0.972 for unprotected nests), but did not significantly affect the number of birds fledged. We observed nest predation by both Black Rats and feral Cats at unprotected nests. Unprotected nest sites had significantly shorter chambers than predator-proofed nest sites, suggesting that while predator-proofing significantly increases nest success for Green Parrots, preferred nest site characteristics have not been preserved through modifications. These findings highlight the importance of assessing the effectiveness of management actions regularly to inform evidence-based decision-making and adaptive management.

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Breeding parameters; breeding success; invasive species; introduced predators; nest protection; predator exclusion

Introduction

Invasive species present a major threat to the conservation of native fauna worldwide (Bellard *et al.* 2016; Doherty *et al.* 2016; Duenas *et al.* 2021). These invasions are almost always facilitated by humans and may be intentional (e.g. Shine 2010) or accidental (Toy and Newfield 2010). Invasive species primarily impact native species through the disruption of natural processes in ecosystems, particularly through predation (Doherty *et al.* 2016) and competition (David *et al.* 2017). The combined impacts have contributed to more than 50% of recent extinctions of mammals, amphibians, reptiles and birds globally (Bellard *et al.* 2016). Currently, 14% of the world's Critically Endangered terrestrial vertebrates are threatened by invasive species, with the Black Rat and feral Cat having the greatest impact worldwide (Doherty *et al.* 2016; Duenas *et al.* 2021). This is particularly true for island-dwelling birds, with nearly 50% of Critically Endangered birds on islands threatened by invasive species (Duenas *et al.* 2021).

Birds require secure nesting sites that are safe from predation (Newton 1994; Lima 2009). Invasive predators can drastically increase nest predation rates, having dire consequences for the breeding output of wild birds (e.g. Heinsohn *et al.* 2015). As a result, conservation managers have devised a variety of techniques to reduce nest predation on wild birds (Gautschi *et al.* 2024). These include lethal predator control (Smith *et al.* 2010), interventions to prevent access by predators (e.g. Tan *et al.* 2015), and interventions to alter predator behaviour (e.g. Norbury *et al.* 2021). While these efforts can improve breeding outcomes for wild birds, their

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effectiveness varies based on factors such as the specific technique used and the species of predator (Gautschi *et al.* 2024). Furthermore, some methods have been associated with unintended consequences, such as nest abandonment (e.g. Pearson *et al.* 2012) and increased predation on adults (e.g. Isaksson *et al.* 2007). As a result, it is crucial that the value of predator interventions is assessed on a case-by-case basis, to ensure management decisions are supported by evidence (Legge 2015; Sutherland and Wordley 2017).

The Norfolk Island Green Parrot provides an important case study for examining the use of nest site modification to address elevated predation from Black Rats and feral Cats in an island ecosystem. Clearing and modification of vegetation following the European settlement of Norfolk Island in 1788 has drastically reduced the species' available breeding habitat (Invasive Species Council and TierraMar 2021), and the introduction of mammalian predators has drastically increased predation on breeding birds (Hicks and Greenwood 1989; Hill 2002). Since the establishment of the Norfolk Island National Park in 1985, substantial efforts have been made to improve breeding outcomes through the modification of existing natural hollows to provide the parrots with secure, predator-proof nest sites (Hicks and Greenwood 1989; Ortiz-Catedral *et al.* 2018). Despite these efforts, the population remains small, continues to fluctuate, and is likely to remain dependent on conservation intervention indefinitely (Department of Climate Change, Energy, the Environment and Water 2024).

The effectiveness of nest protection for Norfolk Island Green Parrots has not been quantified; in the past, newly discovered natural nest sites were modified to be predator-proof as soon as possible (Hill 2002), meaning that there is no historical sample of natural, unprotected nests for statistical comparison. Recent population modelling suggests that a large proportion of birds recruited into the population in recent years have probably fledged from unprotected nest sites (Gautschi *et al.* 2023). This is despite nearly 50% of available predator-proofed nest sites, which should provide greater protection from predators, being unused (Gautschi *et al.* 2022). It is unclear why birds are selecting unprotected sites over predator-proofed sites, and how nests are faring in the absence of nest protection. Here, we compare the characteristics of a sample of predator-proofed nest sites and unprotected nest sites and examine the success rates and productivity of nesting attempts in both nest types. Our primary aim is to determine the efficacy of this long-term conservation measure for the Norfolk Island Green Parrot, and potentially for other species experiencing heightened predation from invasive species. Alongside this, we examine annual variation in the number of nesting attempts and present contemporary descriptive statistics of the species' phenology, clutch size and brood size, as our dataset provides the most complete picture of these aspects of its life history to date.

Methods

Study species and study location

The Norfolk Island Green Parrot (hereafter 'Green Parrot') is a medium sized (~100–140 g; unpublished data), broad-tailed parrot with predominantly green plumage (Forshaw 2010). The species is endemic to Norfolk Island, a small island in the South Pacific Ocean (29°02′S, 167°57′E), with an area of approximately 35 km^2 (Commonwealth of Australia 2025). Breeding habitat is largely restricted to the Mt Pitt section of the Norfolk Island National Park (approximately 460 ha) (Commonwealth of Australia 2025). Reproduction has been recorded in all months of the year in native tree hollows, generally within two metres of the ground, clutch size is 1–8 eggs, incubation takes approximately three weeks, and the nestling period takes 6–7 weeks (Hicks and Greenwood 1989; Hicks and Preece 1991; Hill 2002). Green Parrots have been observed repeatedly using the same nest site or nearby nest sites and producing up to four successful clutches per year (Hicks and Preece 1991; Hill 2002).

Apart from six nesting attempts on private properties, all nesting included in this analysis occurred within the Mount Pitt section of the Norfolk Island National Park and the adjacent Norfolk Island Botanic Gardens. Most nest sites comprise natural hollows that have been modified to prevent predator access, flooding and site degeneration (hereafter referred to as predator-proofing). Nest modifications are highly variable, but commonly involve the use of cement, chicken-wire and metal-sheeting to block access holes, reinforce the nest site, make the external walls difficult to climb, improve drainage and alter the size and location of the entrance hole (Hicks and Greenwood 1989; Gautschi *et al.* 2022). All modified nests are also equipped with an inspection hole to provide access to the base of the nest for monitoring and access to nestlings (Hicks and Greenwood 1989). Examples of a predator-proofed nest site and natural, unprotected nest site are shown in Figure S1.

Nest monitoring

Nest monitoring data were collected between 2013 and 2023. During this period, park staff checked predator-proofed nest sites monthly and increased frequency of checks when nests were found to be active. Intervals between checks of active nests varied depending on resourcing and personnel constraints. Between 2021 and 2023, we undertook additional monitoring of both predator-proofed and unprotected nests (ANU Animal Ethics Permit A2020_13). We actively searched for natural, unprotected nest sites during peak breeding times (February to May) and monitored these when signs of activity were observed. We monitored a subset of both unprotected nest sites ($n = 10$) and predator-proofed nest sites ($n = 9$) with motion activated cameras capturing either still photos (Reconyx Hyperfire HC500 cameras; 2021) or video footage (Reconyx XR6 Ultrafire cameras; 2022–2023). This increased the accuracy of monitoring, while decreasing the need for manual nest checks. Our final sample included 220 nesting attempts (210 predator-proofed and 10 unprotected) at 54 nest sites (46 predator proofed and 8 unprotected).

Reproductive phenology and life history

For our examination of the Green Parrot's reproductive phenology and life history, we only considered nesting attempts in which egg laying was confirmed or a breeding female was disturbed by a predator after settling at a nest but prior to laying ($n = 220$). We estimated the month and year of nest initiation, assuming eggs were laid on every second day, followed by a 21-day incubation period and a 49-day nestling period (Hicks and Greenwood 1989). Where possible, we calculated clutch size, brood size, nest success and nest productivity (see Supplementary Methods). To determine nest fate, we used photo/video evidence where available, or the presence/absence of signs of failure when the nest was last checked. We defined nest success as the fledging of at least one juvenile. To determine whether the number of monthly nesting attempts varied significantly between years, we fitted a generalised linear model (glm) in R v 4.3.1 (R Core Team 2023), with the number of nesting attempts initiated per month as the response variable. Similarly, to test whether time of year had an influence on the number of nesting attempts initiated, we fitted a generalised linear mixed-effects model (glmm) with number of nesting attempts as the response variable, month as the predictor variable and year as a random term, to account for repeated observations of months between years. We tested the explanatory value of each of these models against a corresponding null model, using Akaike information criterion (AIC; Burnham *et al.* 2011).

Nest success and productivity modelling

To examine the influence of predator-proofing on nest success, we modelled daily survival rate (DSR) using the program MARK v10.1 (White and Burnham 1999; Dinsmore *et al.* 2002) and the associated R interface RMark v3.0.0 (Laake 2013). We fitted a univariate model with predator-proofing status as the predictor variable and DSR as the response variable. In addition, we fitted univariate models with five additional predictor variables that we hypothesised could affect the DSR of nesting attempts (year, month, nest site ID, entrance height, chamber depth and wall width). We also fitted a model involving an interaction between year and month to look for seasonal and annual variation. We compared these models with a null model and used AIC to select the most parsimonious model. Given the small sample of unprotected nesting attempts suitable for this analysis ($n = 7$), we were not able to fit multivariate models that included predator-proofing status.

For nest productivity, we used a sample of 178 nesting attempts (see Supplementary Methods for further detail) to fit a saturated glmm, with number of fledglings as the response variable, predator-proofing status, entrance height, chamber depth, wall width, year and month as predictor variables and nest site as a random effect. We then used the dredge function in the package MuMIn v1.47.5 (Bartoń 2023) to compare variations of the saturated model and performed full model averaging on the result.

To examine the likelihood of a Type II statistical errors, we tested the statistical power of our sample to detect differences between predator-proofed and unprotected nests using the R package pwr v1.3 (Champely *et al.* 2020). Power analysis indicated that we had a 53% chance of finding a significant effect for nest protection status if a large effect existed for DSR analysis and nest productivity analysis (Supplementary Methods, Table S1).

Nest characteristics

To identify the similarities and differences between predator-proofed and unprotected nest sites, we compared seven attributes of predator-proofed nest sites recorded by Gautschi *et al.* (2022) with those of unprotected nest sites discovered between 2021 and 2023. We took measurements at unprotected nest sites using the same method presented in Gautschi *et al.* (2022). As unprotected nest sites did not have an inspection hole for access to the base of the nests, some characteristics (e.g. floor diameter) could not always be measured, and average wall width was based only on the wall width at the entrance hole for these nest sites. We compared nest site characteristics using Welch's *t*-tests and adjusted *p*-values using the Bonferroni correction to account for the large number of *t*-tests involved (Armstrong 2014). We also tested the impact of limiting the sample of unprotected nest sites to those that had been used ($n = 8$). Unused unprotected nest sites ($n = 5$) comprised natural sites in which extensive prospecting by adult parrots was observed but egg laying was not confirmed. We tested the statistical power of our sample sizes to detect differences between predator-proofed ($n = 71$) and unprotected nests ($n = 13$). Power analysis estimated that we had a 65–75% chance of finding a significant difference between nest types if a large effect existed (Supplementary Methods, Table S1). The R Script used for all analyses is provided in Supplement 1.

Results

Reproductive phenology and life history

While egg-laying (nest attempt initiation) was recorded in all months of the year, 93% ($n = 195$) of nesting attempts were initiated between December and June. The glmm containing month as the predictor variable and year as a random term outperformed its associated null model (ΔAICc = 142.6). Significantly more nesting attempts were initiated in each month between December and June than during austral spring months (September – November; Figure S2a). The glm containing year as the predictor variable also outperformed its associated null model (ΔAICc = 15.2). We observed a gradual decline in the number of nesting attempts initiated after 2017 and significantly fewer nesting attempts were initiated per month on average in 2021 and 2022 (Figure S2b). The mean clutch size was 5.24 ± 1.68 SD (range = 1–10, $n = 142$) and the mean brood size 3.1 ± 1.26 SD (range = 1–7, $n = 160$). In total, 161 of 220 nesting attempts (72.7%) were successful. Average nest success of predator-proofed nesting attempts was 74.8% (157/210), compared to 40% (4/10) for unprotected nesting attempts. Nesting attempts produced an average of 1.97 ± 1.63 SD fledglings (range = 0–7, $n = 191$).

Nest success and productivity modelling

We calculated daily survival rate (DSR) using a sample of 195 nesting attempts (188 predator-proofed and 7 unprotected) from 44 nest sites (38 predator-proofed and 6 unprotected). For all nesting attempts combined, we estimated a DSR of 0.9945 (95% CI: 0.9927–0.9959, $n = 195$), corresponding to a nest success rate of 68% (over 70 days; Hicks and Greenwood 1989). Of the models we fitted, only the model containing predator-proofing status explained the data significantly better than the null model (ΔAICc = 4.77, Table 1). This model estimated DSR for predator-proofed nesting attempts at 0.995 (95% CI: 0.993–0.996) and for unprotected nesting attempts at 0.972 (95% CI: 0.928–0.99) (Figure 1), which translates to an estimated nest success of 69.9% for predator-proofed nesting attempts and 14.1% for unprotected nesting attempts over a 70-day period. None of the covariates we tested explained variation in nest productivity (Table S2).

Analysis of nest characteristics at unprotected nests

We discovered eight unprotected nest sites in which egg-laying was confirmed, or in which the female was disturbed by predators prior to laying eggs. A further five unprotected sites attracted considerable prospecting behaviour, but we could not confirm egg-laying. The eight used nest sites were in the roots or trunk of four native tree species: *Cordyline obtecta* ($n = 2$), *Nestegis apetala* ($n = 2$), *Lagunaria patersonia* ($n = 1$) and *Cyathea brownii* ($n = 1$), and one introduced tree species: *Olea europaea* ($n = 2$). The additional five nest sites that attracted extensive prospecting behaviour were in the trunks of *Cordyline obtecta* ($n = 2$) and *Nestegis apetala* ($n = 3$). Unprotected nest sites had significantly shorter chambers ($t = 7.84$, $df = 23.27$, p

Table 1. Summary of models of daily survival rate (DSR) for Norfolk Island Green Parrot nesting attempts (= 195).

Model	Parameters	AICc	ΔAICc	Weight	Deviance
Predator-proofing	2	308.01	0	0.72	304.01
Month	10	311.43	3.42	0.13	291.40
Null	1	312.78	4.77	0.07	310.78
Entrance height	2	314.22	6.21	0.03	310.22
Wall width	2	314.77	6.76	0.02	310.76
Chamber depth	2	314.77	6.76	0.02	310.77
Year	11	322.21	14.2	0.00	300.18
Nest site ID	36	332.88	24.87	0.00	260.54
Year*Month	65	355.84	47.83	0.00	224.73

Figure 1. Estimated daily survival rate (DSR) of Norfolk Island Green Parrot nesting attempts by predator-proofing status from the univariate model fitted in MARK (= 195). Error bars indicate 95% confidence intervals.

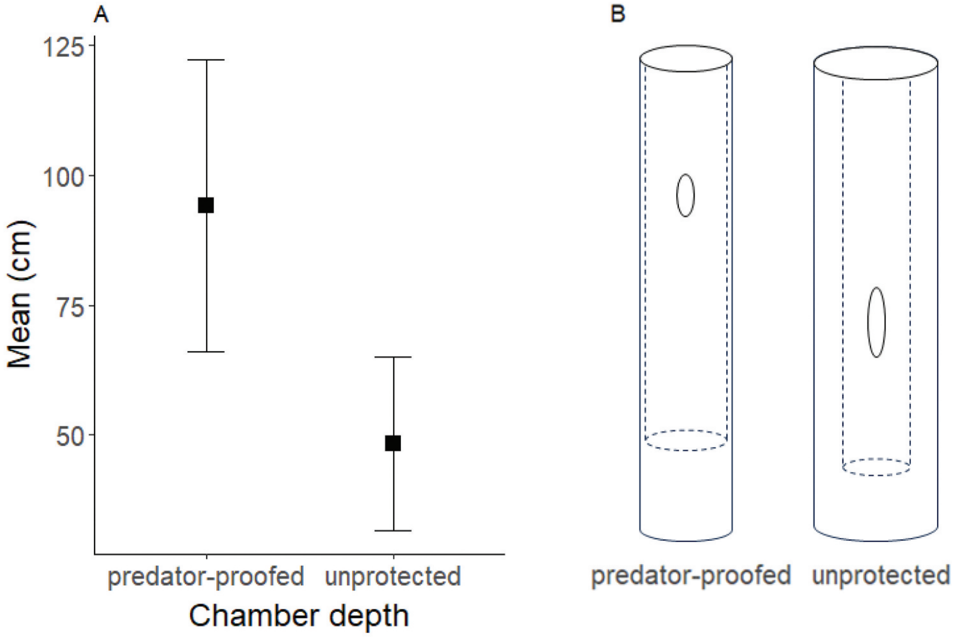

Figure 2. Dimensions of predator-proofed and unprotected Norfolk Island Green Parrot nest sites: A) mean chamber depth ± SD, and B) diagram showing the comparative mean measurements of predator-proofed and unprotected nest sites (diameter at breast height (DBH), entrance height, chamber depth, floor diameter, entrance maximum and entrance minimum).

Table 2. Nest characteristics of all predator-proofed and unprotected Norfolk Island Green Parrot nest sites.

	Predator-proofed (all)		Unprotected (all)		Welch's t-test		
Covariate	Mean (n)	SD	Mean (n)	SD		df	
DBH (cm)	37.2 (71)	14.8	49.7 (13)	39.9	−1.11	12.61	1
Entrance height (cm)	130.5 (71)	41.9	75.2 (13)	82.3	2.37	13.16	0.238
Chamber depth (cm)	94.2 (71)	28.1	48.3 (12)	16.7	7.84	23.27	< 0.001
Floor diameter (cm)	33.2 (71)	11.8	26.9 (10)	10.4	1.76	12.49	0.723
Entrance min. (cm)	6.5 (71)	1.2	6.6 (13)	4.0	−0.05	12.37	1
Entrance max. (cm)	17.5 (71)	5.8	28.1 (13)	18.4	−2.06	12.44	0.423
Wall width (cm)	5.2 (71)	2.4	11.1 (12)	13.3	−1.53	11.12	1

DBH represents tree diameter at breast height.   represents the -value adjusted using the Bonferroni correction. Characteristics with significant differences are bold.

= <0.001) than predator-proofed nest sites (Figure 2a, b, Table 2). Differences in chamber depth remained significant when we restricted the dataset to unprotected nest sites in which egg-laying was confirmed (Table S3). While not statistically significant, unprotected nest sites had more than double the average wall width and nearly half the average entrance height of predator proofed sites, and most characteristics showed greater variability between unprotected sites (Table 2).

Causes of nest failure

The cause of nesting failure was often unclear at predator-proofed nest sites, but suspected causes of failure included: rat predation, nest disturbance by introduced Crimson Rosellas *Platycercus elegans*, usurpation by introduced European Honeybees *Apis mellifera*, weather-related destruction and unexplained abandonment of eggs. Nest monitoring using motion activated cameras enabled the cause of failure to be determined at some unprotected nest sites. Partial or complete failure occurred at seven unprotected nest sites. The causes of complete nest failure were predation ($n = 2$) and flooding ($n = 1$), but three nesting attempts failed for unknown reasons. One nesting attempt suffered partial failure due to predation by a feral Cat.

We recorded one of the complete nest failures due to predation, and the partial nest failure due to predation on camera. A feral Cat killed a well-developed nestling at approximately 8 pm at an unprotected nest site in May 2021 (Figure S3a). The nestling appeared to be near the nest entrance, a tunnel at ground level within the roots of a *Cordyline obtecta*. One nestling had already fledged from this nest, so we still considered this nesting attempt successful. We recorded a second predation event in an unprotected nest site within an *Olea europaea*. We observed two nesting attempts at this site; the first successfully produced three fledglings in February 2022. Cameras recorded the regular occurrence of rats at the nest entrance (~3 m above ground) during both nesting attempts. The second attempt (in May 2022) failed only 5 days after discovery, when a Black Rat was filmed attacking the female (Figure S3b). The female escaped but re-nesting did not occur. We found no eggshells in the nest chamber, meaning egg laying was unconfirmed. A third presumed predation attempt involved a large number of feathers found within a *Cyathea brownii* trunk in May 2022. We discovered this nest because a male Green Parrot was observed nest guarding. We do not know the fate of the female Green Parrot, or the identity of the predator, and we found no evidence of eggs or chicks in the nest. We provide further details of all unprotected nest failures in Table S4. Photo and video monitoring at predator-proofed and unprotected nest sites showed numerous predator visits that did not result in predation events (e.g. Figure S4a, b).

Discussion

Invasive predators present a major threat to the conservation of terrestrial animals (Bellard *et al.* 2016; Doherty *et al.* 2016; Duenas *et al.* 2021). For threatened birds, nest predation can be drastically increased as a result of invasive predators (Heinsohn *et al.* 2015), leading conservation managers to devise a variety of interventions to reduce their impact (Gautschi *et al.* 2024). While these efforts can increase breeding success, their effectiveness varies significantly based on factors such as the method used and the predator species being targeted (Gautschi *et al.* 2024). Predator-proofing of natural Norfolk Island Green Parrot nesting hollows has been used to reduce predation by rats and cats for over 30 years (Hicks and Greenwood 1989). However, the efficacy of this method has not been tested due to the fear of adverse outcomes from leaving newly discovered nests unprotected (Hill 2002). In this study, we used a sample of predator-proofed and unprotected Green Parrot nests to quantify the effectiveness of this management action and compare characteristics of both nest types. We also used this dataset to examine aspects of the species' phenology and life history. Our findings indicate that predator-proofing is effective in increasing Green Parrot nest success. However, our analysis suggests that nest site modifications may not encompass the nest characteristics preferred by breeding birds. We observed moderate, but variable seasonality in breeding, and a noteworthy decrease in nesting attempts in recent years. Below, we discuss the implications of our findings for the future management of the species and the broader field of research.

Nest success and productivity

We found a median clutch size of five (range = 1–10) and a median brood size of three (range = 1–7), which is similar to the range of values reported for other *Cyanoramphus* parrots (Elliott *et al.* 1996; Greene 2003; Theuerkauf *et al.* 2009; Ortiz-Catedral *et al.* 2010), and previous observations of the Green Parrot by Hicks and Preece (1991). Nest productivity does not appear to be influenced by any of the variables tested in our models. Average nest success for Green Parrot nesting attempts was 72.7%, while DSR was 0.995 (corresponding to a nest success rate of 68% over a 70-day nesting period). These rates are within the range of nest success figures reported for its congeners (Elliott *et al.* 1996; Greene 2003; Ortiz Catedral and Brunton 2009). However, estimated DSR was significantly higher for protected nesting attempts (0.995, $n = 188$) than unprotected nesting attempts (0.972, $n = 7$), and the resulting discrepancy between apparent nest success (40%) and nest success derived from DSR (14.1%) was much greater. This is the result of known, protected nests generally being detected and monitored much earlier in the nesting period than previously undiscovered, unprotected nests. This illustrates why daily survival rate is considered an important and less biased measure of overall nest success (Dinsmore *et al.* 2002). Unfortunately, the sample of unprotected nests discovered was small, possibly due to the low levels of breeding observed from 2021 to 2023, and therefore confidence intervals are large. Estimates of statistical power indicated that the statistical power to detect even large effect sizes was limited, suggesting that a larger sample of these nests is required to confidently reject the null hypotheses for nest productivity. Nonetheless, our results indicate that unprotected nests have a lower success rate than their predator-proofed counterparts, with apparent unprotected nest success (40%, $n = 10$) closely resembling the average nest success observed for Yellow-crowned Parakeets in a year of high Stoat *Mustela erminea* density and no predator control (40%, $n = 10$; Rhodes *et al.* 2008). Predation was the most common cause of known nest failure in our sample, with camera monitoring revealing predation by Black Rats and feral Cats at two unprotected nest sites.

Recent population modelling by Gautschi *et al.* (2023) suggests that the majority of the contemporary Green Parrot population hatched in unprotected nest sites; yet, the low observed success rate of unprotected nesting attempts appears to challenge this finding. Nevertheless, inputs used by Gautschi *et al.* (2023) showed that unprotected nests could still be responsible for the majority of the observed population growth if females breeding in these nest sites had a 5% increase in mortality rate, and a 25% decrease in annual productivity compared to birds breeding in predator-proofed nest sites. With repeat nesting events (observed twice in unprotected nest sites), it may be possible for unprotected nests to achieve the productivity levels required to explain recent population growth (Gautschi *et al.* 2023).

Reproductive phenology

Green Parrot nesting attempts were initiated in all calendar months; however, eggs were most commonly laid in February (20% of annual nesting) or May (23%), and most nesting attempts (93%) were initiated between December and June. This breeding season is similar, although slightly later than the breeding seasons reported for other *Cyanoramphus* parrots (Greene 2000, 2003; Ortiz Catedral and Brunton 2009; Ortiz-Catedral et al. 2010, 2013). However, the Yellow-crowned Parakeet *C. auriceps* has also been recorded breeding extensively throughout the year following beech *Nothofagus* spp. mast seeding events (Elliott *et al.* 1996). A lack of clear seasonality is more common among tropical species than those inhabiting higher latitudes, and while a peak in breeding is often observed, year-round breeding of individuals is not uncommon (Stouffer *et al.* 2013). Given the relative stability of Norfolk Island's ocean-moderated climate throughout the year, the annual variability in the number of Green Parrot nesting attempts by calendar month is understandable. However, just 2% of nest attempt initiation occurred during the austral spring. Phipps (1981) noted that reports from 1939 suggest that Green Parrots nested primarily in October. If these observations are accurate, this shift in timing of breeding could reflect Crimson Rosellas proliferating and outcompeting Green Parrots at nest sites in the austral spring (Hicks and Preece 1991; Krebs 1998; Gautschi *et al.* 2022), or a response to changes in climate (Halupka and Halupka 2017). While the change in timing for Green Parrots is noteworthy, our models showed no significant effect of the month of nest attempt initiation on DSR or nest productivity.

A notable trend was the gradual decrease in nesting attempts since 2017 and significant decrease in 2021 and 2022. This change may reflect unmeasured variables, such as weather or the presence of a particular food source, as these factors are crucial for some parrot species (e.g. Lilac-crowned Parrots *Amazona finschi* (Renton and Salinas-Melgoza 2004) and Kākāpo *Strigops habroptila* (Von Hurst *et al.* 2016)). It is worth noting that one of the driest years (second only to 2024) recorded on Norfolk Island since 1891, 2017 (778.6 mm; Bureau of Meteorology 2025), was also the year with the most nesting attempts initiated, while the wettest year on record, 2022 (2,098 mm; Bureau of Meteorology 2025), was the year with the fewest nesting attempts initiated, suggesting a possible link between precipitation and breeding. A negative association between extreme rainfall and body condition has also been observed for the Norfolk Island Morepork (Olsen and Cunningham 2022). As this may reflect a more complex relationship between weather variables and nest use, in-depth climate analysis (e.g. Hidalgo Aranzamendi *et al.* 2019) is warranted.

Nest characteristics

Natural, unprotected nest sites selected by Green Parrots had significantly shorter chambers than predator-proofed nest sites. While nest site characteristics did not appear to impact nest success, they may impact nest usage (Renton *et al.* 2015), and this difference could indicate that shorter chambers are preferred by Green Parrots, given that many predator-proofed nest sites remain unused (Gautschi *et al.* 2022). This preference probably reflects the adaptation of the species to an island free of nest predators where nesting in shallow chambers close to the ground is not a disadvantage. Because a shorter chamber could increase the detectability of visual, olfactory and audial cues and allow access by Norfolk Island's terrestrial mammalian predators, particularly feral Cats, future nest site modifications may need to compromise in creating nest sites that are both attractive to Green Parrots and relatively safe from predators.

While not statistically significant, average unprotected nest walls were more than double the width and entrances nearly half the height of predator proofed nest sites. This provides some support for the findings of Gautschi *et al.* (2022) regarding the preference of Green Parrots for thicker nest walls. In general, there was also greater variability in the attributes of unprotected nest sites, probably reflecting a human preference for the development of relatively uniform nest sites that are deemed safe for nesting and easy to access and monitor. Unfortunately, the relatively small sample of unprotected nest sites we discovered limited the statistical power of these comparisons, but nest site characteristics collected at any natural nest sites discovered in the future can be used to increase confidence in these findings.

Conclusions

Our findings have important implications for the future conservation management of the Green Parrot. Predator-proofed nest sites are clearly superior in promoting breeding success over their unprotected counterparts, and our observations of predation events at unprotected nest sites demonstrate the value of nest modifications. However, predator-proofed nest sites may not encompass the preferred nest site characteristics of Green Parrots, possibly due to modifications made during the predator-proofing process or due to the choice of potential nest sites for modification. Given the findings of recent population modelling and the wide variety of nest sites used by the Green Parrot, it is probable that extensive breeding is occurring outside of protected sites (Gautschi *et al.* 2023). Therefore, enhanced park-wide predator control remains crucial to support the Green Parrot population (Gautschi *et al.* 2023), while simultaneously supporting other threatened species on Norfolk Island (Commonwealth of Australia 2025). Alongside this, productive predator-proofed nest sites should continue to be maintained and monitored, and any newly modified sites should be designed to more closely replicate the characteristics of natural nest sites selected by Green Parrots.

Increasingly, the field of conservation has seen a push towards evidence-based decision-making (Sutherland *et al.* 2004), a particularly important consideration when resources are limited, and conservation stakes high. Yet the use of scientific evidence to support conservation decisions is still lacking in many on-ground projects (Legge 2015; Sutherland and Wordley 2017; Walsh *et al.* 2019). For endangered species, urgent action may be necessary to prevent extinctions before an evidence base can be established (Canessa *et al.* 2020; Stojanovic and Crates 2021). However, without ongoing assessment of the effectiveness of management actions, conservation programs run the risk of perpetuating inefficiencies in the long term (Ferraro *et al.* 2006; Legge 2015). In this study, we tested, for the first time, the efficiency of a management action that has been used for over 30 years. Our study adds to the literature on non-lethal predator interventions for nesting birds (Gautschi *et al.* 2024) and provides an example of successful alleviation of the predation threat posed by the world's most significant invasive predators (Doherty *et al.* 2016; Duenas *et al.* 2021). Nonetheless, we identified areas for development that can improve future conservation efforts for the Norfolk Island Green Parrot. By assessing the effectiveness of management actions, researchers and practitioners can adjust existing methods and improve conservation outcomes for threatened species (e.g. McCarthy and Possingham 2007).

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Author contributions

DG, RH, LO, MW, EDD, DS, NAM and RC conducted fieldwork; DG, DS and RH conducted data analysis; DG, RH, DS, LO, PO, MW, NAM, RC, EDD, LEN and SMB wrote and edited the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on request.

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