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A model of albatross breeding success using passive data collection

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SUMMARY

Remote and inhospitable terrain has long hindered the collection of key demographic data from threatened albatross species at their breeding sites. This study leverages recent advances in passive data collection by using trail cameras to monitor the breeding success of vulnerable Salvin's albatross at the isolated Bounty Islands between 2018 and 2024. Time-lapse imagery was systematically processed into detailed encounter histories for 193 individual nests, covering three key developmental stages: incubation, guard, and post guard. A bespoke hierarchical Bayesian state-space survival model was developed to estimate daily survival rates at each stage, explicitly accounting for imperfect detection, uncertain transitions, and unknown lay and fledge dates. Results revealed low overall breeding success, estimated at just 35% (95% credible interval: 23–48%), driven primarily by poor egg survival (53%; 34–70%) during incubation. This was followed by improved chick survival (67%; 58–75%) across the guard and post-guard stages. This study demonstrates that passive remote sensing, combined with robust statistical modelling, offers a powerful, non-invasive solution to overcoming logistical constraints at remote albatross colonies. However, attempts to assess interannual variation in survival were limited by missing data in some stage–cohort combinations, underscoring the need for continued monitoring to build a completer and more representative dataset. Ongoing data collection will enable more nuanced insights into temporal patterns and potential environmental drivers of survival. The framework developed here can be readily applied to other albatross species where trail camera monitoring is feasible, providing valuable demographic insights to inform conservation efforts.

1. INTRODUCTION

Global albatross populations are in decline, primarily due to threats such as fisheries bycatch, predation by invasive species, competition with commercial fishing operations, and anthropogenic climate change (Cooper et al., 2006; Croxall et al., 2012; Paleczny et al., 2015; Phillips et al., 2016; Pardo et al., 2017; Dias et al., 2019). The life-history traits of these long-lived, slow-breeding species mean their populations recover slowly, increasing their risk of extinction (Clay et al., 2019; Dias et al., 2019; Paleczny et al., 2015; Pardo et al., 2017). Effective conservation of these species requires a robust understanding of their demography and the threats influencing population dynamics, enabling targeted and impactful management interventions (Phillips et al., 2016; Wolfaardt & Phillips, 2020).

Monitoring demographic rates in wide-ranging species such as albatrosses is particularly challenging and generally feasible only at breeding colonies, where individuals gather predictably (Phillips et al., 2016). Many albatrosses nest in harsh, isolated environments that provide protection from mammalian predators and access to productive foraging grounds (Bakker et al., 2018). However, such sites are often difficult for researchers to access reliably, limiting our ability to collect detailed demographic data, especially across the full duration of the breeding season. Breeding success, a key demographic rate, remains particularly poorly understood at the most remote colonies, where egg and chick survival may be highly sensitive to environmental variability, including fluctuations in food availability and changing climatic conditions (Cleeland et al., 2020; Michael et al., 2017; Mills et al., 2020; Rackete et al., 2021; Rolland et al., 2010; Thomson et al., 2015; Weimerskirch, 2018; Weimerskirch et al., 2001).

While long-lived seabirds like albatrosses are typically more sensitive to changes in adult survival than breeding success (Caravaggi et al., 2019; Cleeland et al., 2021; Prince et al., 1994), the latter remains an important demographic parameter, particularly for understanding population resilience in the face of compounding pressures. As K-selected species, albatrosses invest heavily in a single offspring per breeding attempt, with extended parental care that spans many months. Some species even breed biennially, skipping the year following successful reproduction to recover from its energetic costs (Jouventin & Dobson, 2002). Although many populations can tolerate short-term breeding failures, sustained reductions in reproductive output can still have serious consequences, especially when compounded by other threats. For example, Oppel et al., (2022) demonstrated that prolonged predation pressure led to a cryptic population decline in a long-lived seabird, despite stable adult survival. While certain threats to breeding success, such as invasive predators, can be mitigated through targeted management, more diffuse pressures like food scarcity and climate change are harder to detect and address (Cleeland et al. 2021). Understanding the role of these drivers in limiting reproductive output requires consistent, long-term monitoring across a range of sites.

New technologies offer promising solutions for passively collecting detailed demographic data from remote locations, enhancing our ability to understand and ultimately protect vulnerable populations. In particular, high-quality, commercially available automated “trail” cameras have expanded what is feasible to monitor at remote albatross colonies (Black, 2019; Edney & Wood, 2021). These cameras are are ideal for passive time-lapse photography, allowing researchers to capture regular images of individual nests throughout the entire breeding season. Previously, collecting such temporally detailed data would have required researchers to remain on-site for months at a time, an impractical and often impossible undertaking. In contrast, trail cameras reduce both logistical burden and wildlife

disturbance, requiring only brief visits to deploy and retrieve the units (Rexer-Huber et al., 2021).

Aotearoa New Zealand is home to 13 albatross taxa (Robertson et al., 2021), all of which breed on remote offshore islands, with 10 species breeding in the sub-Antarctic region (Taylor, 2000). Sub-Antarctic breeding sites are characterised by harsh terrain, extreme weather, and minimal infrastructure, making monitoring efforts logistically demanding, financially expensive, and typically restricted to short seasonal visits. To support investigations into albatross breeding success, the Department of Conservation has deployed trail cameras at multiple breeding colonies throughout New Zealand's sub-Antarctic region (Elliott et al., 2023; Mattern, 2022, 2024a, 2024b; Mischler et al., 2024; Mischler & Wickes, 2023; Rexer-Huber et al., 2021; Sagar et al., 2024). These include colonies of White-capped albatross (*Thalassarche steadi*), Southern Buller's albatross (*Thalassarche bulleri bulleri*), Southern Royal albatross (*Diomedea epomophora*), Grey-headed albatross (*Thalassarche chrysostoma*), Light-mantled Sooty albatross (*Phoebetria palpebrata*), and Salvin's albatross (*Thalassarche salvini*).

Recent research by Rexer-Huber et al., (2021) reported surprisingly low breeding success in Salvin's albatross, estimated at just 28% (95% CI: 13–44), based on survival analysis from two breeding seasons of trail camera imagery. These findings underscore potential knowledge gaps in breeding outcomes across New Zealand's remote albatross colonies. Salvin's albatross exemplifies the challenges of monitoring in sub-Antarctic environments. This species has only two permanent breeding sites (Taylor, 2000), the Bounty Islands and the Western Chain of the Snares Islands, both of which are difficult to access and lack infrastructure to support extended fieldwork. Approximately 96% of the global population nests on the Bounty Islands, a cluster of 22 small granite outcrops located 640 km east of New Zealand's South Island (Sagar et al., 2011). These islands are steep, barren, and extremely exposed, with few safe landing sites, requiring continuous boat support for research operations.

Salvin's albatross are classified as *Nationally Critical* under New Zealand's Threat Classification System (Robertson et al., 2021), are highly susceptible to fisheries bycatch (Abraham et al., 2016; Richard et al., 2017; Edwards et al., 2023; Peatman et al., 2023), and have undergone a significant long-term population decline (Sagar et al., 2015). Together, these factors highlight the urgent need for effective, low-impact and automated monitoring tools, such as trail cameras, to improve our understanding of demographic trends in this group of vulnerable species. However, while trail cameras offer a powerful solution for monitoring certain population parameters, the resulting imagery requires careful processing and tailored analytical approaches to extract and interpret survival information effectively.

In this chapter, we develop a hierarchical Bayesian state-space model to estimate daily survival rates (DSR) across three key breeding stages, incubation, guard, and post-guard, using capture–mark–recapture (CMR) data derived from trail camera images. The model builds on the Bayesian framework of Schmidt et al., (2010), incorporating Mayfield's exposure-based method (Mayfield, 1961; 1975) to estimate survival probabilities throughout the breeding cycle. The model adopts the Cormack–Jolly–Seber (CJS: Cormack, 1964; Jolly, 1965; Seber, 1965) survival framework, separating the biological survival process from the observation process through a latent state structure. This design accounts for imperfect detection and variation in camera performance, for example, when eggs are obscured by incubating adults or when adverse weather renders images unusable, and can accommodate uncertainty in lay dates, stage transitions, and fledge outcomes. To support the modelling,

we developed a systematic method for extracting survival data from trail camera images, capable of processing large datasets with varying numbers of nests per frame. This approach constructs nest-specific encounter-histories suitable for survival analysis.

Leveraging these detailed encounter-histories, the model also estimates the timing of developmental transitions, from egg to guard to post-guard, using interval-censored data informed by direct observations. This enables nuanced estimation of stage durations and accurate attribution of survival to specific stages. We apply this approach to an expanded dataset of Salvin's albatross breeding attempts, producing updated estimates of breeding success and revealing interannual variation in nest survival. Ultimately, this flexible modelling framework provides a robust and adaptable tool for estimating true breeding success from passive monitoring data, with broad applicability to other albatross species and other surface-breeders on remote breeding colonies.

2. METHODS

Data Collection

Images of nesting Salvin's albatross for this study were captured using Swift Enduro trail cameras deployed on Proclamation Island in the Bounty Islands archipelago. Cameras were active periodically between October 2018 and October 2024, with five to six units deployed at any given time. The cameras were serviced on five occasions during this period, with new units installed at each visit to maximise operational lifespan. To support extended functionality, each camera was equipped with high-capacity SD cards (SanDisk 32GB, 90MB/s) and long-life batteries (Energizer Ultimate Lithium AA). Cameras were securely bolted to vertical rock faces and aimed at areas of high nesting density to maximise the number of monitored nests per camera. After 2020, the cameras were bolted to overhanging rock faces to avoid damage caused by New Zealand Fur Seals *(Arctocephalus forsteri)* as described by Rexer-Huber et al., (2021). Cameras were spaced to avoid overlapping fields of view, and images were captured at hourly intervals between 04:00 and 22:00.

Image Processing

We processed the image data using the open-source software digiKam (digiKam developers team, 2025), which enabled tagging and organising observations via hierarchical metadata. Nest survival and developmental stages were recorded using structured tags stored in the Extensible Metadata Platform (XMP) section of each image file. To generate encounter-history data, we reviewed images from each camera sequentially. When an egg or chick was visibly alive and present, we applied a hierarchical tag indicating the nest and its stage: Egg (E), Chick (C), Post-Guard (PG), Dead (D), or Not Classifiable (NC). Each nest was assigned a unique identifier (e.g., N1), and each image could receive one tag per nest. Since a single image could show up to 45 nests, this hierarchical tagging system helped manage complexity and maintain consistency. Because our analysis required daily survival data, we tagged each nest only once per day. If a nest's status (survival and stage) was confirmed in the first image of the day, we did not tag it again in subsequent images on that day. If the status of a nest could not be confirmed on a given day despite reviewing multiple images, we left it untagged, resulting in an (NA) value that was explicitly handled as detection uncertainty in the survival model.

To ensure consistent nest identification across images and over time, we used annotated screen overlays created with Ink2Go (EyePower Games Private Limited, 2018). These

overlays displayed fixed nest positions and remained visible during image processing in digiKam, helping to maintain tagging accuracy. Once tagging was complete, we extracted the image metadata for analysis using ExifTool (Harvey, 2025) within the R environment (R Core Team, 2025). For each breeding season, we reviewed all images taken between August 1st and April 28th. Throughout this thesis, each breeding season is referred to by the year in which that cohort's chicks would fledge (Wolfaardt & Phillips, 2020).

Modelling

To estimate egg and chick survival from our encounter-history data, we developed a hierarchical Bayesian state-space model using Just Another Gibbs Sampler (JAGS: Plummer, 2003) via the rJAGS (Plummer, 2025) package within the R programming environment (R Core Team, 2025). The model followed the Cormack–Jolly–Seber (CJS) capture–mark–recapture framework (Cormack, 1964; Jolly, 1965; Seber, 1965) to estimate DSRs, adapting a Bayesian nesting success model originally proposed by Schmidt et al., (2010) in a similar manner to (Fischer et al., 2021). This approach incorporates a latent state to represent the true, unobserved survival status of each individual, allowing separation of the biological process of survival from imperfect detection in the observations. we modelled DSRs across three stages between laying and fledging: incubation (egg survival), guard (chicks attended by a parent just after hatching), and post-guard (chicks left unattended at the nest). We assumed constant survival within each stage, but allowed survival rates to vary between stages. Time (within stages) or other covariates were not included in the baseline model structure. Breeding success was calculated as the product of stage-specific DSR, each raised to the power of its corresponding stage duration. To account for uncertainty, breeding success was estimated using posterior samples of DSR, generating a distribution of success probabilities across all stages.

Each egg or chick was allowed to transition between stages independently, based on its encounter-history data. This approach enabled the model to track the current stage of each individual and to attribute survival or mortality events to the appropriate stage. To ensure transitions occurred within time frames consistent with image-based observations, We used interval censoring. For example, if an individual was observed as an egg and then as a chick one week later, the model restricted the transition to that interval. Within this range, the timing was informed by global transition distributions, which incorporated prior knowledge of typical stage durations and were refined using other observed transitions from across our dataset. Sharing transition information across individuals, while still allowing for individual variation, was particularly important for estimating transitions for individuals with missing observations.

Fledging was not directly observable in the trail camera images, as chicks often leave their nest area prior to fledging and may not return. To account for this, we used a joint distribution approach in which the model probabilistically determined whether a chick had fledged or died based on how far it had progressed through the post-guard period when it was last observed. For example, if a chick disappeared midway through the post-guard stage, the model was more likely to assign its fate as mortality. In contrast, if a chick was last seen near the end of the post-guard period, the model was more likely to infer successful fledging. Once fledging was inferred, the individual's latent state was no longer updated, as fledged chicks were not expected to reappear in subsequent images.

To investigate interannual variation in survival, and consequently breeding success, We explored three iterations of the survival model, each increasing in the complexity of how

survival was allowed to vary across stages and cohorts. These models were motivated by biological expectations that breeding conditions differ between seasons, influencing egg-survival and chick-rearing success. However, our encounter-history data for Salvin's albatross included gaps across several stage–cohort combinations, largely due to differences in the timing and duration of camera deployments. To address these data gaps while still producing robust survival estimates, We implemented a tiered modelling approach. The first model estimated survival by stage only, pooling data across all cohorts, i.e., the base model. The second model incorporated additive cohort effects alongside stage effects, allowing survival to vary by both stage and cohort. The third model introduced a full interaction between stage and cohort, enabling survival to vary independently for each stage–cohort combination.

Model 1: Stage Effects Only

The first model included effects for stage (incubation, guard, and post-guard) but excluded cohort effects. Data from all cohorts were pooled to estimate stage-specific DSRs. We used uniform Beta distributions as priors for survival and detection probabilities, allowing the data to dominate inference for these parameters.

To inform global transition timing, We incorporated prior knowledge from related studies. The prior for hatching was centred on the 14th of November, based on data from Proclamation Island in 1997. Guard duration was set at 27 days, informed by observations of the closely related Shy albatross (*Thalassarche cauta*; Hedd & Gales, 2005), and the post-guard period was assumed to last 123 days, based on average fledging and guard-end-dates reported by Rexer-Huber et al., (2021). To assess the model's sensitivity to these informative priors, we re-ran it using uniform, uninformative priors for the global transition parameters while keeping all other priors constant (Table 2.1). These uniform priors allowed the data to have greater influence over the posterior estimates.

Table 1. Prior distributions used for global transition timing parameters under two prior formulations: informative and uniform within a reasonable range. All normal priors were truncated at zero.

Parameter	Informative Prior	Uniform Prior
Hatching	Normal(104, SD = 5)	Uniform(74, 134)
Guard Duration	Normal(27, SD = 4)	Uniform(7, 47)
Post-Guard Duration	Normal(122, SD = 4)	Uniform(92, 152)

Model 2: Additive Stage and Cohort Effects

Model 2 (Appendix 2B) introduced additive effects of cohort alongside stage effects, allowing DSRs to vary both between developmental stages and across cohorts. This structure reflects ecological expectations that survival may fluctuate annually due to external factors such as weather or food availability in particular years, while still maintaining consistent differences in survival between stages. we estimated survival using a hierarchical logistic model that included stage-specific baseline means and a shared cohort-level deviation. To constrain

these deviations while allowing for data-driven flexibility, we used a moderately informative half-Student's *t* prior ($t(0, 1, 3)$, truncated at 0) on the standard deviation of the cohort effects (SD_φ). While the prior is centred at zero on the logit scale, it reflects an expectation of modest variation around a baseline DSR of approximately 0.950. The scale parameter of 1 was chosen because we considered it a reasonable assumption for the extent of year-to-year variation in survival. All other priors, including those for detection and stage transitions, matched those used in Model 1.

After reviewing our model outputs, we ran a second sensitivity test, this time using Model 2, to evaluate the influence of the half-Student's *t* prior on the standard deviation of the cohort effects (SD_φ). Specifically, we compared posterior estimates of stage and cohort-level survival under three alternative prior formulations for (SD_φ) with increasing degrees of informativeness: a mild prior ($t(0, 0.5, 3)$), a moderate prior ($t(0, 1, 3)$), and a highly informative prior ($t(0, 5, 3)$). All priors were truncated at zero. This allowed me to assess how strongly the estimated variability in survival across cohorts was shaped by prior assumptions, particularly in stage–cohort combinations with little to no data.

Model 3: Stage-by-Cohort Interactions

Model 3 (Appendix 2C) relaxed assumptions further by allowing survival to vary independently for each stage–cohort combination. This fully factorial structure accounted for potential interactions between stage and cohort, such as situations where egg survival was poor in one cohort, while chick survival was more poor in another. This structure was motivated by biological expectations that some developmental stages may be more sensitive to environmental variability than others. We retained the same prior settings used in Model 2, including the moderately informative half-Student's *t* prior on the variability of survival parameters (SD_φ). While this approach supported meaningful variation where supported by the data, we anticipated it would struggle to converge on estimates in stage–cohort combinations with little or no data, relying heavily on the priors to guide inference in these cases.

To evaluate model performance and ensure accurate estimation of survival, detection, and transition parameters, we tested each model using simulated data. This allowed me to validate model structure and assess whether parameter estimates were recoverable under controlled conditions. All models were implemented using JAGS (Plummer, 2003) using the rJAGS (Plummer, 2025) package within the R programming environment (R Core Team, 2025). We used three Markov Chain Monte Carlo (MCMC) chains for each model and initially ran 100,000 iterations per chain. For some models, particularly the more complex formulations, 150,000 iterations were required to achieve adequate convergence. We discarded the first half of each chain as burn-in, ensuring that posterior estimates were based on well-mixed, stable samples.

4. RESULTS

We constructed 193 encounter-histories of eggs and chicks from trail camera images of Salvin's albatross across five breeding seasons over the period 2019 to 2025. However, due to the timing of camera deployments, servicing schedules, and occasional equipment failures, not all encounter-histories spanned the entire breeding cycle. Only two cohorts (2019 and 2023) were monitored continuously across all three developmental stages. In contrast, data from 2020 and 2025 covered only the incubation period, whereas observations for the 2024 cohort began in the early post-guard stage and continued through to fledging (Table 2.2).

Table 2.2. Summary of observation data by cohort. Camera Days represents the total number of days cameras were active. Number of Nests is the count of nests contributing to survival analysis. Incubation, Guard, and Post-Guard indicate the number of observations recorded during each stage of the breeding, exclude NA (not seen) or NC (not classifiable) tags. Observed Deaths refers to confirmed mortalities and excludes individuals that simply went missing.

Cohort	Camera Days	Number of Nests	Incubation	Guard	Post-Guard	Observed Deaths
2019	576	38	43	139	883	18
2020	240	5	8	-	-	1
2023	636	111	34	757	3,823	15
2024	273	25	-	-	1,599	-
2025	273	14	19	-	-	1
Total	1,998	193	104	896	6,305	35

The first model (Model 1), which estimated stage-specific survival across all cohorts, yielded an overall breeding success estimate of 0.352 (95% CI: 0.225–0.479) for Salvin's albatross at the Bounty Islands (Figure 2.1). This estimate was informed by stage-specific survival probabilities:

- Egg survival was estimated at 0.526 (95% CI: 0.344–0.697), based on a DSR of 0.991 (95% CI: 0.985–0.995) over a 73-day incubation period.
- Guard stage survival was substantially higher at 0.960 (95% CI: 0.915–0.989), reflecting a high DSR of 0.998 (95% CI: 0.996–1.000) over a much shorter period of 22.1 days (95% CI: 20.8–23.4).
- Post-guard chick survival was estimated at 0.697 (95% CI: 0.614–0.774), based on a DSR of 0.997 (95% CI: 0.996–0.998) across a longer duration of 122.4 days (95% CI: 120.8–124.0).

The mean hatching date was estimated to be November 16th (95% CI: November 14–18), with the end of the guard stage occurring around December 8th (95% CI: December 6–10). Mean fledging date was estimated at April 9th (95% CI: April 7–12). The duration of chick rearing, the guard and post-guard durations combined, was estimated to last 144.5 days

(95% CI: 142.5–126.5) from laying to fledging. This model structure highlighted the very low detection probability of eggs from trail camera images, estimated at just 0.016 (95% CI: 0.011–0.024), primarily due to visual obstruction by incubating adults. As a result, we did not attempt to estimate mean laying date or incubation duration directly from the data. Instead, we back-calculated the mean laying date to be September 4th (95% CI: September 2–6), based on a 73-day incubation period reported for the closely related Shy albatross (Hedd & Gales, 2005). Detection probabilities were substantially higher during the guard (0.405; 95% CI: 0.381–0.429) and post-guard (0.937; 95% CI: 0.931–0.943) stages, improving the model's ability to estimate transitions between these stages.

The sensitivity analysis demonstrated that Model 1 was generally robust to different prior assumptions on transition timing. Posterior estimates of stage-specific survival and global transition timing remained consistent when informative priors were replaced with uniform priors, indicating that the results were well supported by the data (Figure 2.2). Based on this robustness, we retained the informative priors for transition timing in all subsequent modelling.

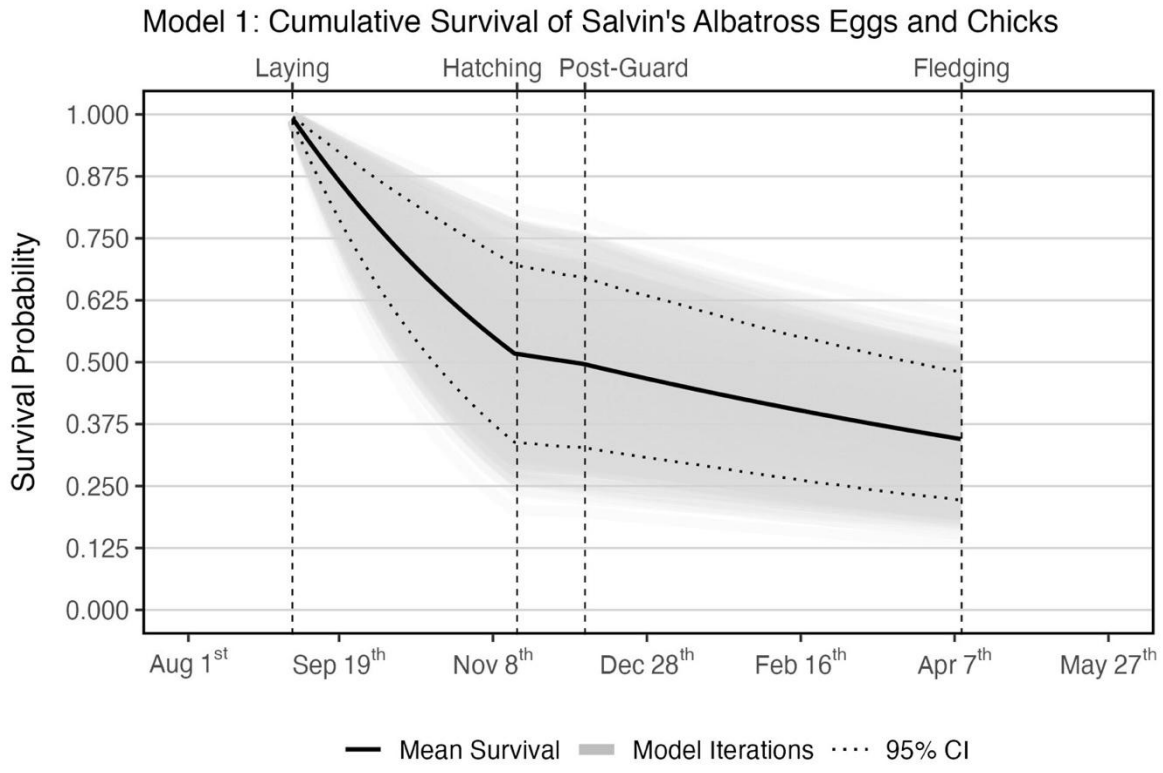

Figure 1 Cumulative survival of Salvin's albatross from laying through fledging on Proclamation Island was calculated as the product of stage-specific daily survival rates (DSR), each raised to the power of its respective stage duration. For the graph, this cumulative product was tracked at each daily time step. The black line represents the posterior mean, while 3,000 individual grey lines show draws from the posterior distribution, illustrating overall model uncertainty. Dashed vertical lines indicate the posterior mean transition points between stages.

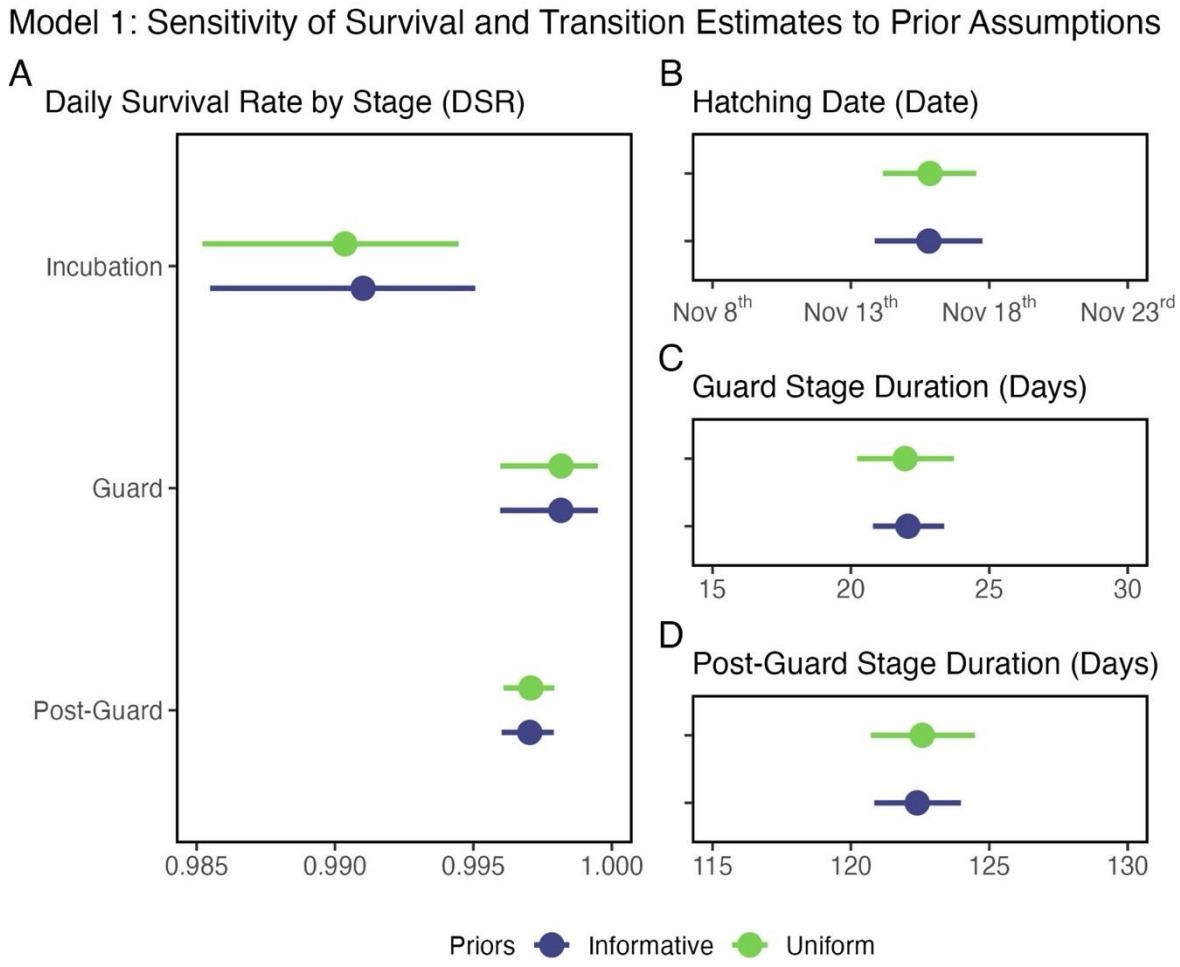

Figure 2. Sensitivity of survival and transition estimates to prior assumptions for global transition timing parameters. Panel A shows stage-specific daily survival rate (DSR) estimates for incubation, guard, and post-guard stages under two prior formulations: *Informative* (normal priors based on published literature) and *Flat* (uniform priors over plausible ranges). Panels B–D show posterior estimates for the global transition timing parameters: hatching date (B), guard stage duration (C), and post-guard stage duration (D). Points represent posterior means, and horizontal bars show associated 95% credible intervals.

Our investigation into intra-annual variation in survival using Models 2 and 3 revealed that both structures encountered difficulties in producing biologically reasonable survival estimates in stage–cohort combinations with sparse or missing data (Figure 2.3). Model 2, which included additive effects of stage and cohort, produced more plausible estimates than Model 3 in data-poor combinations, benefiting from its ability to share information across stages within each cohort. However, even this model struggled to produce biologically credible estimates in combinations with limited data. These low or highly variable DSR estimates resulted in unrealistic estimates of breeding success (Figure 2.4). Only two of the five cohorts, 2019 (0.244 95% CI: 0.121-0.395) and 2023 (0.327 95% CI: 0.155-0.513), displayed reliable estimate of overall breeding success when using Model 2 (Table 2.2 and Figure 2.4). Our sensitivity analysis showed that Model 2 was largely robust to different prior choices on the standard deviation of cohort effects (SD_{φ}), with only minor differences in survival estimates across prior settings (Figure 2.5).

Model 3, which allowed fully factorial interactions between stage and cohort, proved to be even more sensitive to data gaps. While it successfully estimated survival for stage–cohort combinations with sufficient observations, MCMC estimation failed to adequately converge in combinations with no data (Figure 2.3).

Table 3. Summary of stage-specific survival estimates from Model 2, which included additive effects of stage (Incubation, Guard, and Post-Guard) and cohort. Note the very wide credible intervals for survival estimates in stage–cohort combinations with limited data (see Table 2.2), which result in unreliable estimates of overall breeding success, as shown in Figure 2.4.

Cohort	Incubation Survival	Guard Survival	Post-Guard Survival	Overall Breeding Success
2019	0.4 (0.23-0.60)	0.95 (0.89-0.99)	0.62 (0.44-0.77)	0.24 (0.12-0.39)
2020	0.17 (0.00-0.56)	0.84 (0.38-0.98)	0.34 (0.00-0.77)	0.09 (0.00-0.39)
2023	0.49 (0.24-0.73)	0.96 (0.92-0.99)	0.69 (0.60-0.78)	0.33 (0.15-0.51)
2024	0.72 (0.29-0.99)	0.98 (0.93-1.00)	0.85 (0.62-1.00)	0.62 (0.18-0.99)
2025	0.41 (0.02-0.83)	0.94 (0.74-0.99)	0.6 (0.07-0.90)	0.28 (0.00-0.72)

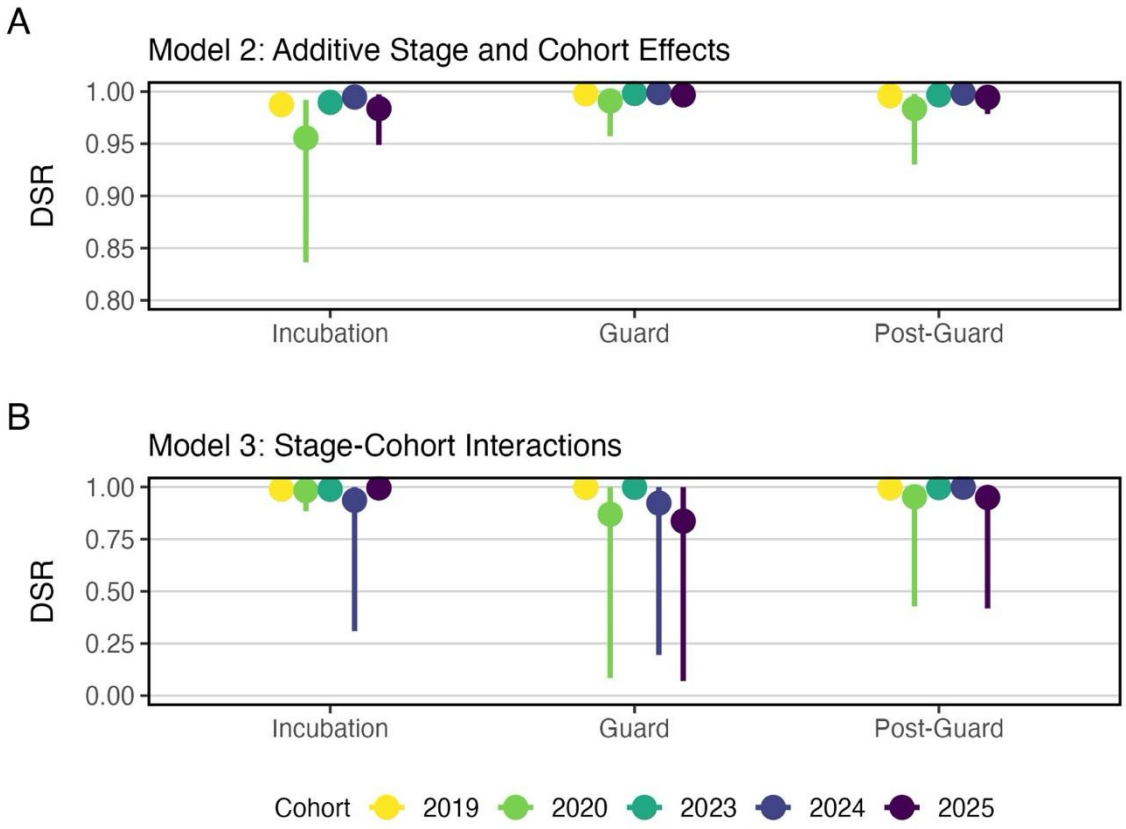

Figure 3. Daily Survival Rates (DSR) for each stage–cohort combination under Model 2 (A) and Model 3 (B). Points represent posterior means, with vertical lines indicating 95% credible intervals. Estimates are grouped by developmental stage (incubation, guard, post-guard) and colour-coded by cohort. Model 2 incorporates additive effects of stage and cohort, while Model 3 allows for full interactions between stage and cohort. Y-axis scales differ between panels to better visualise variation in estimates.

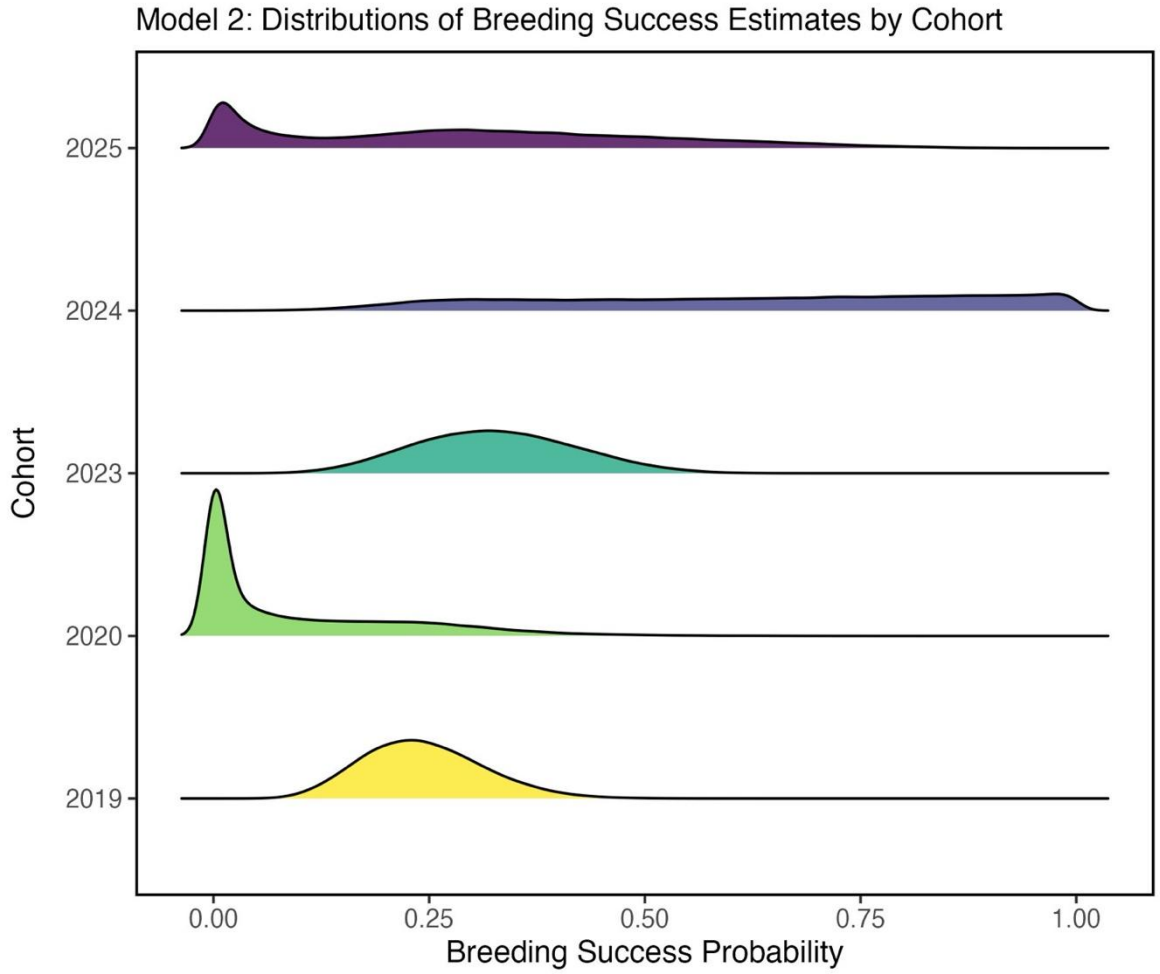

Figure 4. Distributions of breeding success estimates for Salvin's albatross across five cohorts using DSR outputs from Model 2. Each ridge represents the probability distribution of breeding success, calculated as the product of stage-specific daily survival rates raised to their respective stage durations (incubation = 73 days, guard = 22 days, post-guard = 122 days). The distributions for cohorts 2020, 2024, and 2025 display how unrealistic estimates of daily survival rates compound across stages and result in unreliable breeding success estimates. While the 2019 and 2023 show well centred distributions with reasonable levels of uncertainty.

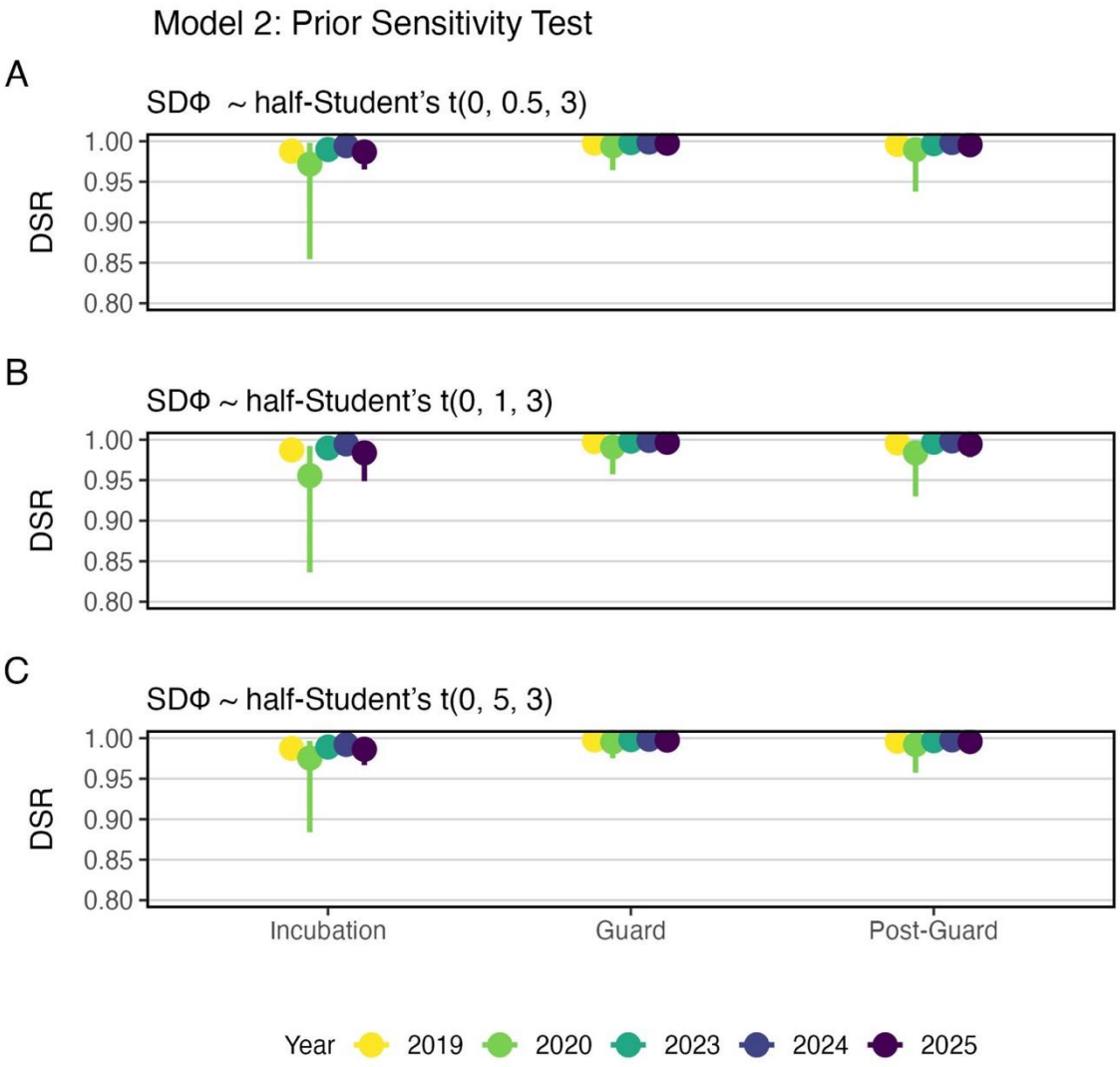

Figure 5. Sensitivity analysis of Model 2 to alternative prior specifications for the standard deviation of cohort effects (SDφ). Posterior estimates of stage- and cohort-level survival are shown under three increasingly informative half-Student's *t* priors on SDφ: mild (*t*(0, 0.5, 3)), moderate (*t*(0, 1, 3)), and highly informative (*t*(0, 5, 3)), all truncated at zero. Results indicate that survival estimates are largely robust to prior choice, with only minor differences across settings, even in stage–cohort combinations with sparse data.

5. DISCUSSION

Our analysis revealed low overall breeding success in Salvin's albatross at the Bounty Islands. When data were pooled across cohorts (Model 1), only 35% (95% CI: 23–48%) of breeding attempts resulted in a fledged chick. This outcome was largely due to low egg survival during the 73-day incubation stage (53%; 95% CI: 34–70%), followed by higher chick survival across the 144-day guard and post-guard stages (67%; 95% CI: 58–75%). However, more detailed investigations (Models 2 and 3) into inter-annual variation in breeding success were hindered by missing data. In particular, posterior DSR estimates were sometimes highly uncertain in stage-cohort combinations with missing data, resulting in unrealistically low or skewed estimates of breeding success when exponentiated by the duration of their respective stages (Figure 2.4). While imposing highly informative priors on the variability of survival parameter (SD_{φ}) could potentially address the issue of missing data for both models 2 and 3, doing so risks misrepresenting the true level of uncertainty in the data. A more appropriate and robust solution is to continue expanding the dataset, thereby improving estimates of interannual variation and reducing reliance on poorly informed stage–cohort combinations. Therefore, we place greater confidence in the findings of Model 1 and the cohort-specific breeding success estimates for 2019 and 2023 derived from Model 2, as these cohorts are supported by plenty of data. Although Model 3 offers a flexible structure by allowing survival to vary independently across stages and cohorts, its inability to share survival information across stage–cohort combinations makes it particularly sensitive to missing data. With a larger dataset and the exclusion of stage–cohort combinations lacking observations, Model 3 could become a more viable framework for future analyses.

Our estimate of overall breeding success from Model 1 (0.352; 95% CI: 0.225–0.479) reinforces the low breeding success first reported by Rexer-Huber et al., (2021), who estimated breeding success from the 2019 and 2020 cohorts at 0.276 (95% CI: 0.129–0.442). Our cohort-specific estimate for 2019 (0.244 95% CI: 0.121-0.395) aligns even more closely with their findings. These similarities are reassuring, as both studies used the same trail camera imagery from the 2019 and 2020 cohorts; however, we re-analysed all images to construct encounter-histories appropriate for our model. While our 2019 estimate is slightly lower than the combined estimate by Rexer-Huber et al., (2021), both our 2023 cohort-specific estimate (0.327 95% CI: 0.155-0.513) and the overall breeding success estimate are higher. This suggests that breeding success in 2019 and 2020 may have been below average. However, the dataset for the 2020 cohort is limited, with data only covering the incubation period and informed by just three trail cameras that remained functional a year after their initial deployment.

While the findings of these two studies are similar, our modelling approach differs substantially from that of Rexer-Huber et al., (2021), who analyse DSR for each cohort separately. Their model selection process supported an intra-stage time-varying DSR structure for the 2019 cohort, which included data from late incubation through to fledging. In contrast, the best-supported model for their 2020 cohort, which was limited to early incubation records, assumed constant DSR. Based on their findings, Rexer-Huber et al., (2021) concluded that survival was lowest during late incubation, hatching, and early chick rearing, particularly from mid-October into November.

In contrast, our approach does not attempt to correlate survival with specific time points. Instead, we assume constant DSR within the three clearly defined developmental stages: incubation, guard, and post-guard. A key strength of our framework is the ability to assign latent records of survival and mortality directly to a specific stage, based on transitions

observed in individual encounter-histories. This additional stage-specific resolution suggests that the low survival reported during October–November by Rexer-Huber et al., (2021) may be better explained by stage-specific mortality patterns rather than calendar time. We found that survival was lowest during the incubation stage, highest during the guard stage (immediately after hatching), and moderate during the post-guard stage. A plausible explanation, supported by both modelling approaches, is that elevated mortality occurs around the time of hatching. Hatching is a particularly vulnerable time for birds (Marshall et al., 2023), as complications originating earlier in incubation, such as dead or underdeveloped embryos, may only become apparent at this point. These issues can result in embryo death during hatching or prompt adults to abandon non-viable eggs, leading to a sharp increase in mortality near hatch (Assersohn et al., 2021; Morland et al., 2024). In our framework, most hatching-related mortality is attributed to the incubation-stage, as it occurs before the individual has transitioned into guard-stage, thereby lowering the DSR estimates at the incubation-stage. In contrast, Rexer-Huber et al., (2021) attributed mortality to daily time intervals, regardless of whether the failed individual was an egg or a chick.

Past field observations also support high mortality during incubation and hatching. Sagar et al., (2015) reported a 34% mortality rate during Salvin's albatross hatching at the Bounty Islands in 1997, and Clark, (1996) estimated that only 50% of Salvin's albatross eggs survived through incubation and hatching to become chicks on the Snares Western Chain, based on two consecutive nest counts.

Poor survival during incubation may be influenced by environmental conditions at the two Salvin's albatross breeding colonies. Both island groups are exposed, and rocky, offering limited nesting material. On the Bounty Islands, Salvin's albatrosses compete for both space and nesting material and are sometimes found nesting in poorly constructed scrapes (Robertson & Van Tets, 1982), which may increase the risk of egg loss. In this context, the higher DSR observed during the guard-stage is ecologically plausible: chicks that survive hatching are less fragile than eggs yet still receive close protection from their parents, unlike chicks in the later post-guard stage. Rexer-Huber et al., (2021) hypothesised that disturbance by New Zealand Fur Seals could explain the low DSR observed in October–November. We found no evidence of such disturbance in the trail camera images we reviewed. However, because images were captured at hourly intervals, it was often difficult to determine the precise cause of nest failures. Overall, the growing evidence suggests that poor egg survival is a major limiting factor in breeding success for Salvin's albatross. Whether this reflects a natural baseline for the species or is being exacerbated by additional pressures, such as disturbance, climate change, or reduced food availability, remains unclear.

This research, alongside the work of Rexer-Huber et al., (2021), represents a significant advancement in our understanding of Salvin's albatross breeding success. For instance, the New Zealand seabird risk assessment by Abraham et al., (2016) relied on expert elicitation to set population parameters for many albatross species due to a lack of direct data. This included a breeding success estimate for Salvin's albatross of 0.467 (95% CI: 0.348–0.580), which was not empirically derived but rather expert elicited. In comparison to other albatross species, the breeding success observed in Salvin's albatross appears notably low. A study by Cleeland et al., (2021) estimated breeding success for four albatross species breeding on Macquarie Island over a 19-year period (1995–2014). Black-browed albatross (*Thalassarche melanophris*) had the lowest breeding success at 51.6% (± 1.5%), followed by Light-mantled albatross (*Phoebetria palpebrata*) at 57.1% (± 2.4%), Grey-headed albatross (*Thalassarche*

chrysostoma) at 57.7% (± 1.3%), and Wandering albatross (*Diomedea exulans*) at 61.7% (± 4.1%). These estimates were derived from long-term capture–mark–recapture data, which included resighting of nesting adults and assessments of breeding status and fledging success. Although the methodologies differ, these data are broadly comparable to our estimates for Salvin's albatross.

Our estimates of stage duration (guard-stage; 22.1 days; 95% CI: 20.8–23.4 and post-guard; 122.4 days; 95% CI: 120.8–124.0) provide the first directly modelled estimates of chick-rearing stage lengths for Salvin's albatross. These estimates are broadly consistent, although slightly shorter, than those reported by Hedd and Gales, (2005) for Shy albatross on Albatross Island, in Southern Australia. In their study, they reported an incubation duration of 73 days, a guard stage of 27.3 days, and a post-guard stage of 127 days. Unfortunately, we were unable to generate an updated estimate for incubation duration in Salvin's albatross. This is primarily due to the poor visibility of eggs in trail camera imagery, which limits accurate determination of laying and hatching dates. Additionally, adult albatrosses often begin nest-building well before egg-laying, further obscuring when eggs could have been laid. Rexer-Huber et al., (2021) raised the possibility that Salvin's albatross hatching dates have shifted ~7 days earlier since 1978 (Robertson & Van Tets, 1982; Sagar et al., 2015). However, their estimates of hatching timing were derived by back-calculating from the end of the guard-stage, identified in trail camera images, using a guard duration of 27 days based on Shy albatross (Hedd & Gales, 2005). If the true guard duration for Salvin's albatross is closer to 22 days, as our modelling suggests, then the evidence for a temporal shift in breeding phenology becomes less compelling.

The collection of daily encounter-histories, as used in this study, would not be possible without trail cameras or similar passive automated imaging systems. The time-series imagery they provide far exceeds what human observers could feasibly collect at such remote sites over extended periods. However, there are important limitations and considerations to keep in mind when employing these technologies. Reviewing large quantities of time-series images is highly time-consuming. We recommend using image tagging software we did in this research, where observations are written directly into the image metadata. This approach greatly facilitates later data extraction, editing, and verification. For studies focused on albatross breeding success, it is also highly advisable to record the content and stage of each nest visible in the camera's field of view at the time of deployment. These initial records can serve as the first observation in each individual's encounter-history and are especially critical for estimating egg survival. Due to their low detectability, eggs are often not visible in images for several weeks, limiting the amount of usable survival data available for the incubation period unless their presence is documented by observers at the time of camera deployment. Finally, where feasible, trail camera servicing or deployment should be scheduled between breeding seasons. Doing so helps ensure complete encounter-histories, which will improve the accuracy of both stage transition and stage duration estimates. However, this may be challenging given the remoteness of these islands and the need to balance multiple competing research objectives, of which most will likely require birds to be present on the colony.

6. CONCLUSION

Trail cameras offer a powerful solution for monitoring seabird populations at remote and logistically challenging breeding colonies. At the Bounty Islands, where traditional fieldwork is limited by harsh terrain and restricted access, they have enabled the collection of detailed nest histories for Salvin's albatross across entire breeding seasons. When paired with appropriate analytical tools, such as those developed in this chapter, trail camera data can greatly enhance our understanding of key demographic parameters, including breeding success, that drive albatross population dynamics. The models and methods presented here are readily transferable to other albatross species already being monitored with trail cameras across New Zealand's sub-Antarctic islands. As a range of threats continue to impact these vulnerable populations, adopting new tools to inform and prioritise conservation efforts will be critical for more effective management.

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