APPARENT SURVIVAL AMONG ADULT LEACH'S STORM PETRELS *HYDROBATES LEUCORHOUS* ON A COLONY MANAGED FOR PREDATORS IN NOVA SCOTIA, CANADA

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ABSTRACT

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Population declines of Leach's Storm Petrels *Hydrobates leucorhous* in the western Atlantic have both led to the species' recent assessment as Threatened in Canada and contributed to a Vulnerable designation by the IUCN. Limited information suggests low adult survival rates are an important contributing factor. Off eastern Nova Scotia, Canada, Country Island is managed for avian predators and mustelids to protect nesting endangered Roseate Terns *Sterna dougallii*. The island also hosts a colony of Leach's Storm Petrels. In 2016, a capture-mark-recapture program was initiated for storm petrels, from which we estimated apparent survival and recapture probabilities for 571 breeding birds using data collected from 2016 to 2021. Models with a time-since-marking effect were consistently ranked higher than those without; annual apparent survival estimates in the first year after capture were lower than in subsequent years, presumably due to some captured birds not returning to the study area. Apparent survival in the years subsequent to first capture was lowest in forested areas with no understorey vegetation, slightly higher in forested areas with fern understorey, and highest in open areas with dense fern cover. While the mechanism driving habitat differences in adult survival is unknown, predation pressure may be strongest in forested areas with open understorey where it is easier for predators to find burrow entrances. Although apparent adult survival rates were higher than reported previously for nearby Bon Portage Island where predation is significant, Country Island may represent a best-case scenario for Leach's Storm Petrel in Atlantic Canada, since predators are managed and adult mortality from avian predators is relatively low at this site. Even so, survival rates at Country Island are lower than those reported previously at two Pacific colonies and provide evidence that adult survival rates of Leach's Storm Petrels in eastern Canada are depressed.

Key words: apparent survival, capture-mark-recapture, Leach's Storm Petrel, *Hydrobates leucorhous*, Nova Scotia, Atlantic Canada

INTRODUCTION

Leach's Storm Petrel *Hydrobates leucorhous* (hereafter 'storm petrel') is a small, abundant, and wide-ranging seabird that breeds mainly on small offshore islands in the North Pacific and North Atlantic. Atlantic Canada hosts approximately one third of the global population of approximately 16 million individuals (Pollet *et al.* 2021). Surveys at eight major colonies in the provinces of Newfoundland, Nova Scotia, and New Brunswick indicate that the number of individuals has declined by 54% over the past three generations (44 years) and that the rate of decline is increasing (COSEWIC 2020). Leach's Storm Petrel was recently designated as Threatened by Canada's Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and is being considered for listing under the federal Species at Risk Act. Despite Canada's responsibility for this species, there is limited information on the drivers of these declines. Colony size reconstructions spanning thousands of years for two large colonies in Atlantic Canada show that, although regional oceanographic conditions play a role in colony trajectories (Duda *et al.* 2022), the natural dynamics of storm petrels has been severely disrupted since European settlement began (Duda *et al.* 2020a, 2020c), indicating that anthropogenic drivers could have a role in the recent declines.

Storm petrels, like all seabirds, are relatively long-lived with delayed sexual maturity and typically low reproductive output. Thus, reductions in adult survival rate can have severe consequences for lifetime reproductive success and population trends (Warham 1990, 1996). Low annual adult survival has been suggested as a factor leading to observed population declines in Atlantic Canada (COSEWIC 2020). These declines are partly influenced by avian predators at several of the largest breeding colonies, particularly large gulls (American Herring Gull *Larus smithsoniansus*, Great Black-backed Gull *Larus marinus*) and corvids (American Crow *Corvus brachyrhynchos*, Northern Raven *Corvus corax*; COSEWIC 2020). Despite nesting in burrows and being strictly nocturnal at the colony, storm petrels are predated by gulls and corvids that either dig out burrows or capture birds at night, when breeders leave/return to their burrows or non-breeders prospect for nesting sites (Stenhouse & Montevecchi 2000, Hoeg *et al.* 2021). Additional factors with the potential to reduce adult survival are encountered off the breeding colonies, including major shifts in the Atlantic food web and impacts from lighted structures both offshore and onshore (Gjerdrum *et al.* 2021, Wilhelm *et al.* 2020).

On the breeding colonies in Atlantic Canada, nest site habitat ranges from densely canopied coniferous forest to open fern and grass meadow, all with varying soil depth, compaction, and moisture content (Stenhouse & Montevecchi 2000, Fricke *et al.* 2015, Wilhelm *et al.* 2015). Choice of burrow location can be limited by both preferred habitat availability and risk of avian predation (d'Entremont *et al.* 2020). For example, on some islands where gulls nest in open habitat, storm petrels predominantly burrow within the forests (Stenhouse & Montevecchi 2000; Wilhelm *et al.* 2015), whereas in the absence of gull colonies, storm petrels may burrow in higher densities in open fern and grass habitats (Wilhelm *et al.* 2020). In fact, burrowing and soil enrichment by storm petrels leads to vegetative changes towards their preferred open and grass habitats (Duda *et al.* 2020b). On Kent Island in the Bay of Fundy, which hosts one of the largest American Herring Gull colonies in Atlantic Canada, occupied storm petrel burrows were mostly found in areas dominated by fern or shrub with no associated forest regrowth or nearby nesting gulls (d'Entremont *et al.* 2020). It follows that the influence of habitat quality, availability, and avian predator presence on burrow-site selection is complex, dynamic, and highly site-specific.

The aim of this study was to derive survival estimates for storm petrels breeding on Country Island, Nova Scotia, Canada, where avian predation has been relatively minimal due to active deterrence efforts over the past two decades and where storm petrels burrow in a variety of habitats. In 2013, the storm petrel colony was estimated to number 24 460 mature individuals (95% confidence interval (CI): 17 204–31 716; Wilhelm 2017), making it one of only 11 sites in Atlantic Canada to host significant numbers of this species (i.e., > 20 000 mature individuals; COSEWIC 2020) and the second largest breeding colony in Nova Scotia. We interpret storm petrel survival rates in light of the unique features of this colony relative to elsewhere in the region.

METHODS

Study site

Country Island is an uninhabited island (total area of 0.2 km^2) in Guysborough County, on the Atlantic coast of Nova Scotia, Canada

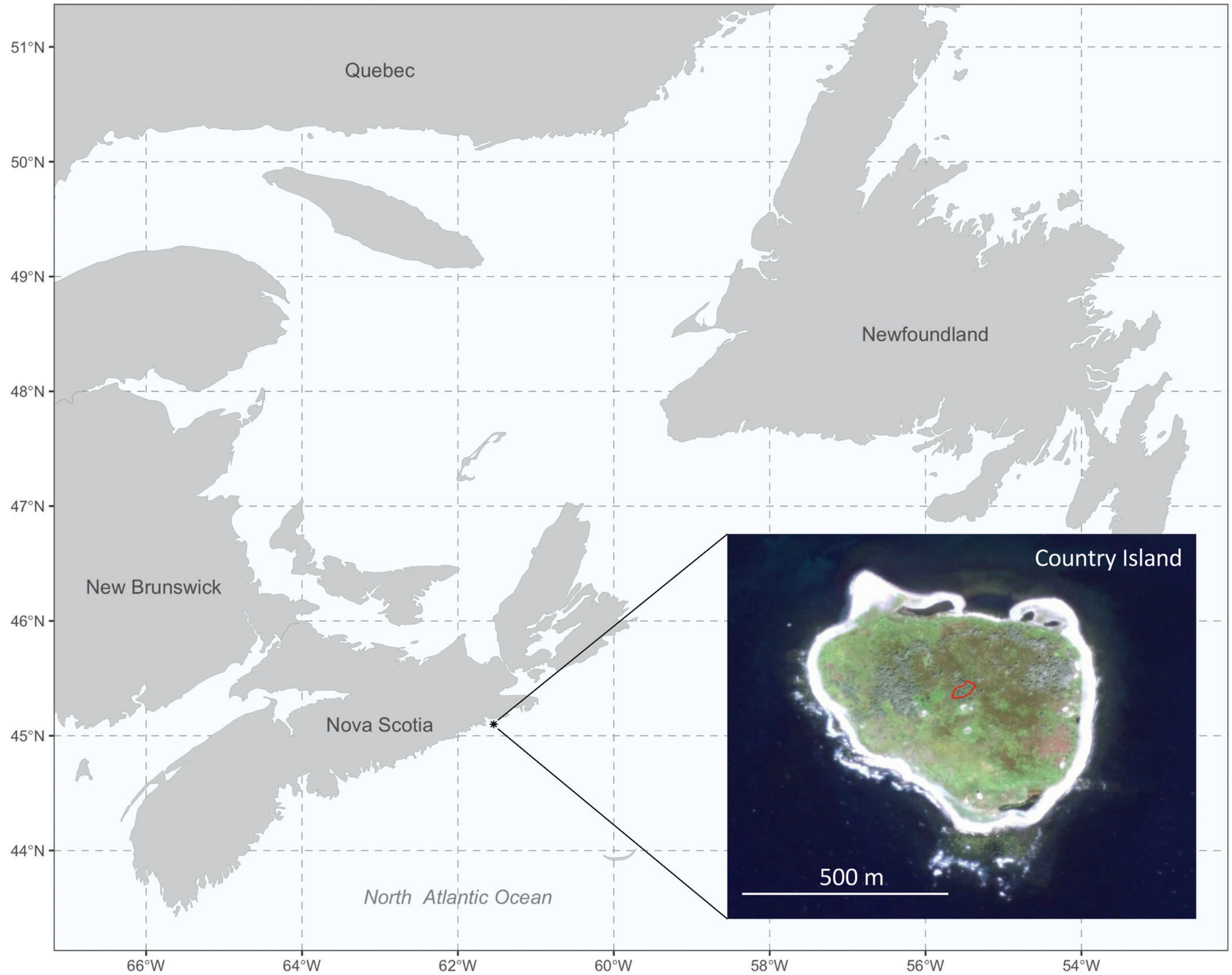

Fig. 1. Map of eastern Canada showing the location of our study site, Country Island in Nova Scotia. The inset shows Google Earth satellite imagery (Google Earth Pro, v.7.3.2.5776) with a red polygon depicting the area of the monitored survival study plots in the centre of the island.

(45.10°N, 061.54°W; Fig. 1). Low-lying and flat, its diverse habitat includes cobble and boulder beaches, stands of White Spruce *Picea alba*, and vegetation such as open heath-scrub, Black Raspberry *Rubus occidentalis* L., various *Angelica* spp., ferns, and tall grasses. The study site is a multi-species seabird colony that also hosts significant populations of Arctic and Common terns (*Sterna paradisaea* and *S. hirundo*, respectively), as well as a small but significant number of endangered Roseate Terns (*S. dougallii*; Wilhelm 2017). In the past, gull and corvid predation at this site caused 50% declines in the number of Common and Arctic tern breeding pairs between two successive breeding seasons, and a reduction to just one Roseate Tern pair (Leonard *et al.* 2004). This led to the initiation of a predator management program in 1998 focused on non-lethal approaches, including deterrence and harassment of potential avian and mammalian predators via human presence, pyrotechnics, and destruction of corvid and gull nests. During the period 1998–2019, these consistent efforts in May through July prevented all gulls and most corvids from successfully nesting on the island, and the main Arctic and Common tern colony rebounded in response (McKnight *et al.* 2018, Canadian Wildlife Service 2019). Predator control was focused on protecting terns (primarily Roseate Terns), so management efforts occurred only during the tern breeding period, leaving three months (August to October) during which storm petrels were breeding on the island but predators were not controlled. In 2020 and 2021, predator management was not conducted on the island due to the COVID-19 pandemic, so predation pressure may have increased in those years.

Capture-mark-recapture monitoring

In 2016, capture-mark-recapture (CMR) plots were established for storm petrels. The plots were located in a small area (perimeter of 130 m) in the centre of the island, in a mix of spruce forest and primarily Bracken Ferns *Pteridium aquilinum* with some tall grasses (Fig. 1). Initially, 100 active burrows distributed in clusters (plots) of varying size and habitat composition were located and marked with unique identifiers. Over time, as new burrows were discovered, inspected, and found to be active, they were uniquely marked and added to those monitored. As of 2021, there were 235 routinely monitored burrows within the study area, including all original plots and burrows (17 plots, averaging 14 burrows per plot). Around 21 June each year, which is after the mean lay date determined by d'Entremont *et al.* (2020), marked burrows were first checked for incubating adults. Any newly captured birds were banded with standardized stainless steel bands, and recaptured birds had their band number recorded. Active burrow entrances were then covered by a lattice of ferns, such that burrow activity could be quickly assessed during a second check six days later. If the lattice was disturbed, an incubation-duty change over may have occurred and the burrow was inspected for the presence of a second adult. If the lattice was found to be intact, the burrow was left alone to avoid repeat disruption. Despite efforts to minimize disruptions, some birds were encountered twice in one breeding season.

Adult survival analysis

We estimated annual apparent survival using a Cormack-Jolly-Seber (CJS) model (Lebreton *et al.* 1992) applied to six years of capture-mark-recapture data. We used Program MARK (MARK version 6.0, White & Burnham 1999) within the "Rmark" package (Laake 2014) in R 4.0.2 (R Development Core Team 2014). Multiple captures within a breeding season were collapsed to a single annual encounter. The CJS open population model allows estimation of time-varying apparent survival (ϕ_t; probability an individual survives the interval between sampling occasions year t to year t+1 (i.e., breeding seasons) and recapture probability (p_t; probability of being recaptured if alive at each sampling occasion t given it is alive and present at the study site; Kendall *et al.* 2013).

In addition to modelling time-variation in ϕ and p, we also considered an effect of burrow habitat on the ϕ parameter. Plots and burrows therein were categorized into three distinct habitat types based on the dominant understorey and overstorey: (1) bare peat soil beneath spruce forest with 50–100% canopy cover (30% of monitored burrows), (2) predominantly fern vegetation beneath spruce forest with 50–100% canopy cover (37% of monitored burrows), or (3) predominantly fern vegetation beneath an open canopy with < 25% canopy cover (33% of monitored burrows). Each captured bird was assigned a habitat based on the burrow habitat in which they were most often encountered. Storm petrels are monogamous with high nest-site fidelity, generally returning to the same nesting burrow each year to raise a single chick (Pollet *et al.* 2021). Of the 309 adults recaptured at least once over the course of this study, 26% were found in more than one burrow but only 4% switched habitats between recaptures. Moreover, of these 15 habitat switchers, 10 were instances in which birds were found in two burrows of different habitats within the same breeding season, suggesting a temporary visit to a neighbour or burrow prospecting rather than a true burrow switch.

Prior to model selection, we tested the CMR data for violations of CJS assumptions using the package "R2ucare" (Gimenez *et al.* 2018). There was no evidence that time since last capture affected recapture probabilities (i.e., trap-dependence; TEST2.CT, $p = 0.16$), but there was weak evidence for a difference in apparent survival rates immediately following the first marking occasion (TEST3.SR, $p = 0.06$). However, clear violations of assumptions may be difficult to detect with a small number of sampling occasions, and both disturbance and capture effects have been documented at a number of Leach's Storm Petrel colonies (Blackmer *et al.* 2004, Rennie *et al.* 2020). Therefore, we included a time-since-marking (TSM) effect in our models (described as 'transience' by Pradel *et al.* 1997), which allowed the apparent survival of birds in the year following their first capture to differ from their survival in subsequent years. We did not consider interactive effects because time-specific effects on habitat or transience would be difficult to estimate and interpret, given the limited time series of five recapture occasions, and we do not expect the TSM effect to differ by habitat. Our global model then included the additive effects of TSM, habitat (*hab*), and time (*t*) on apparent survival, along with time-varying recapture probability: $\{\phi_{TSM+hab+t}\, p_t\}$. We assessed the goodness of fit to our global model using a bootstrap $\hat{c}$ approach to calculate a variance inflation factor of $\hat{c} = 1.08$, which indicated only minor residual overdispersion after including the TSM effect (White & Burnham 1999, Cooch & White 2017). Model selection was based on Quasi-Akaike's Information Criterion adjusted for small sample size ($QAIC_c$), which assigns a further penalty for the number of parameters in a model based on $\hat{c}$ adjustment (Akaike 1973, Burnham & Anderson 2002). We compared the models in the candidate model set via $\Delta QAIC_c$, where the best-fit model has the lowest $QAIC_c$ value, as well as relative Akaike model weights (w_i), which sum to 1 and provide an index of support for each model relative to the total candidate model set (Burnham & Anderson 2002). Our candidate model set considered 14 models, including model structures with time-varying and time-invariant recapture probability (p_t and $p.$) and survival (ϕ_t and $\phi.$); effects of TSM and habitat alone on survival (ϕ_{TSM} and ϕ_{hab}); and additive combinations of TSM, habitat, and time effects on survival. Parameter estimates are reported on the real scale with standard error (SE) and 95% confidence interval (CI) with the following notation: estimate ± SE [lower 95% CI, upper 95% CI]. β-estimates, the linear predictors modeled on the logit scale, are also provided to measure the effect size of relevant parameters.

RESULTS

During the study period (2016–2021), a sample of 571 banded adult storm petrels provided 583 recaptures (Table 1). Of those birds that were newly captured and banded prior to 2021 (n = 466 birds, with the possibility of recapture during the study), approximately one third nested in each of three understorey:overstorey habitat combinations (36% in soil:forest, 33% in fern:forest, 31% in fern:none). The relatively small number of birds that were newly banded or recaptured in 2020 (n = 122) in comparison with 2021 (n = 270) was due to implications of the COVID-19 pandemic on 2020 fieldwork logistics (Table 1). Limitations on the number of field days and personnel in 2020 allowed for only 13% of 211 monitored burrows to be checked twice and 50% to be checked once; 37% were not checked and no new burrows were added. A full field campaign for survival-plot monitoring resumed in 2021, when 94% of monitored burrows were checked twice, 6% were checked once, and 14 new burrows were both added and checked twice.

Among our 14 candidate CJS models, the top-ranked model $\{\phi_{TSM+hab}\, p_t\}$ garnered 68% of model support. In this model, apparent survival probability showed TSM and burrow habitat effects, and recapture probability varied over time (Table 2). Annual recapture probability varied over time, as expected, given that recapture effort varied across years, ranging between p = 0.35 ± 0.03 [0.29, 0.41] in 2020 and p = 0.61 ± 0.05 [0.51, 0.71] in 2021 (Fig. 2). Apparent survival in the years after first capture was lowest in habitat with bare soil understorey and forested canopy cover overstorey (ϕ = 0.87 ± 0.03 [0.79, 0.92], Fig. 2). The habitat effect showed clear differences compared to fern understorey with no canopy cover (β = 0.65 ± 0.26 [0.13, 1.16]) but not compared to fern understorey with forested overstorey (ϕ = 0.88 ± 0.03 [0.81, 0.93]), where the effect size did not differ from zero (β = 0.12 ± 0.23 [−0.34, 0.57]). Apparent survival was highest in habitat with fern understorey and no canopy cover (ϕ = 0.93 ± 0.03 [0.86, −0.96], Fig. 2); the habitat effect indicated differences compared to both fern understorey with no canopy cover (β = 0.65 ± 0.26 [0.13, 1.16]) and fern understorey with forested overstorey (β = 0.53 ± 0.27 [0.01, 1.06]). Most of the remaining model support (16%) included only TSM on survival $\{\phi_{TSM}\, p_t\}$, but it was > 2.0 $\Delta QAIC_c$ from the top model (Table 2). Apparent survival was lower in the first year after capture (ϕ = 0.77 ± 0.03 [0.71, 0.82]) relative to subsequent years (ϕ = 0.89 ± 0.03 [0.83, 0.93]); the size of this effect clearly differed from zero (β = 0.86 ± 0.34 [0.20, 1.52]).

TABLE 1
Reduced m-array showing when and how many adult Leach's Storm Petrels *Hydrobates leucorhous* were recaptured for the first time following release at Country Island, Nova Scotia, Canada, 2016–2021

		Recaptured following release					
Year	**Released**[a]	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**
2016	135	60	17	5	8	2	92
2017	228	0	90	53	9	12	164
2018	185	0	0	98	22	13	133
2019	214	0	0	0	56	68	124
2020	122	0	0	0	0	70	70

[a] Released at a particular occasion (year released); includes both storm petrels that were newly captured/banded and those that were previously banded and recaptured at that occasion.

DISCUSSION

Adult survival rates estimated for storm petrels on Country Island, although higher than other recent estimates from Atlantic Canada, are in line with the depressed trend across the region. At numerous breeding colonies, survival probability has been estimated between 0.78 and 0.86 (COSEWIC 2020), which is lower than typical rates for long-lived seabirds (> 0.9; Warham 1996, Hamer *et al.* 2001) and well below those of two storm petrel colonies of the same species in the eastern North Pacific (average 0.975; Rennie *et al.* 2020). We found a strong effect of TSM on apparent survival (i.e., lower survival in the first year following capture than in subsequent years), similar to those reported from other colonies (Ainley *et al.* 1990, Rennie *et al.* 2020). This indicates either sensitivity of some storm petrels to the disturbance of capture at the burrow and subsequent handling (Blackmer *et al.* 2004) or the presence of birds only loosely associated with the burrows in which they were first captured. We also present evidence that adult apparent survival varies with burrow habitat type at Country Island, with the

TABLE 2
Cormack-Jolly-Seber model results used to model the effects of time since marking (*TSM*), burrow habitat (*hab*), and annual variation (*t*) on apparent survival (ϕ) and recapture (*p*) probabilities of adult Leach's Storm Petrels *Hydrobates leucorhous* monitored during 2016–2021 on Country Island, Nova Scotia, Canada. The notation (.) indicates that the parameter is treated as constant.

Model	$\Delta QAICc$[a]	w_i[b]	QDeviance	Parameters
$\phi_{TSM+hab}\, p_t$	0	0.67	178.8	9
$\phi_{TSM}\, p_t$	2.86	0.16	185.7	7
$\phi_{TSM+hab+t}\, p_t$	3.81	0.10	174.3	13
$\phi_{hab}\, p_t$	5.37	0.04	186.2	8
$\phi.\, p_t$	7.18	0.02	194.1	6
$\phi.\, p.$	50.1	0.00	243.0	2

[a] $\Delta QAIC_c$ is the difference between a given model and the model with the lowest small sample size adjusted Quasi-Akaike's Information Criterion ($QAIC_c$) value. Models were corrected for minor overdispersion at $\hat{c}$ = 1.08.

[b] From the candidate set of 14 models, only those with Akaike weights (w_i) ≥ 0.01 are reported here, with the exception of the null model $\{\phi.\ p.\}$, which ranked last. The global model $\{\phi_{TSM+hab+t}\, p_t\}$ ranked third.

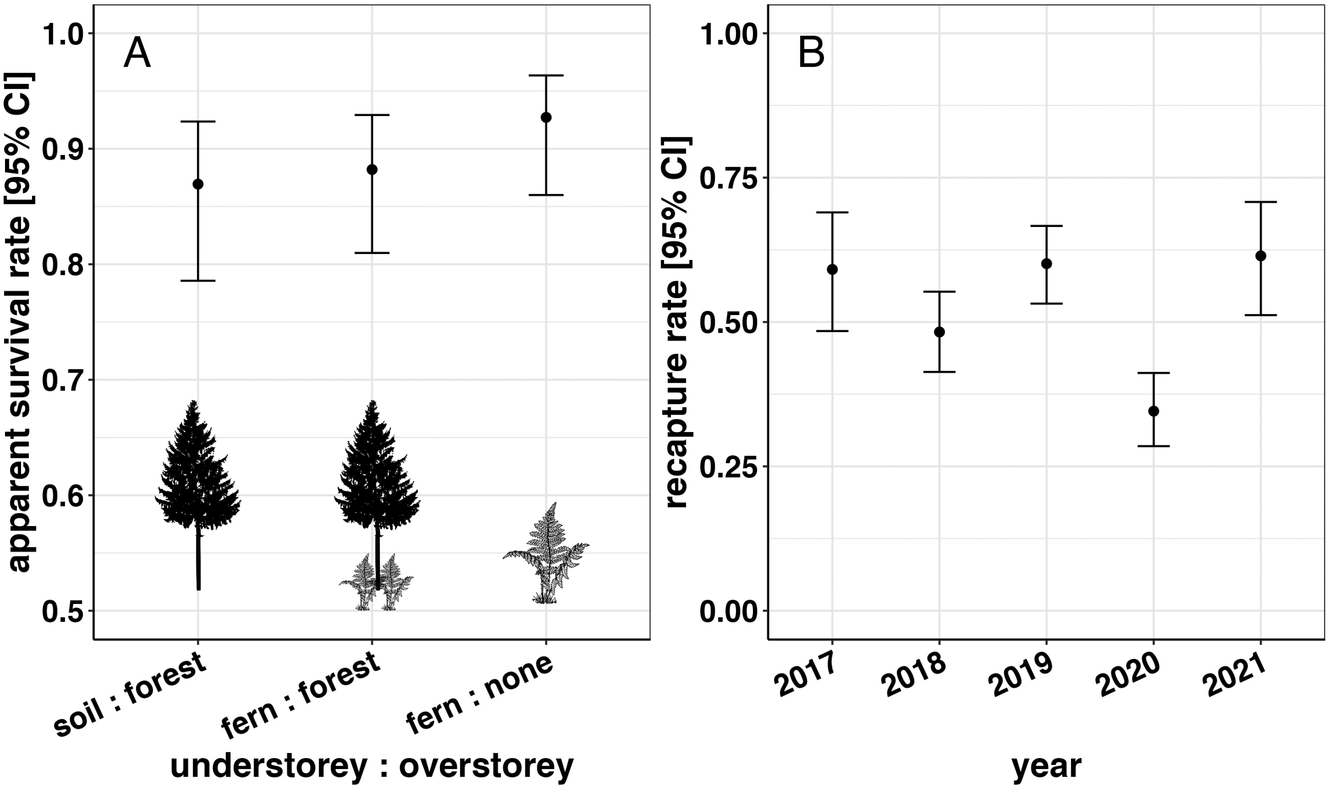

Fig. 2. Parameter estimates from the top model $\{\phi_{TSM+hab}\, p_t\}$. (A) Estimates of non-transient apparent survival rate or probability (95% confidence interval) as a function of burrow habitat described by a combination of understorey (soil surface or fern vegetation) and overstorey (spruce forest canopy cover or open canopy with no cover) traits. (B) Temporal variation in recapture rates or probability (95% confidence interval).

lowest survival rates occurring in forested areas with no understorey vegetation and the highest rates in open areas with dense fern cover.

Considerations in estimating storm petrel survival

Apparent survival in the year immediately following marking was notably lower than in the years subsequent. Conventionally, the apparent survival rates calculated for subsequent years is considered a better estimate of true survival because the population of birds captured for this first time contains some proportion of transients, which are individuals not strongly attached to the study site (e.g., prospecting and newly recruiting birds; Pradel *et al.* 1997). A TSM effect may also reflect storm petrels' sensitivity to disturbance at the colony (Blackmer *et al.* 2004), leading to some birds not tolerating the initial capture event and moving to another site. While efforts have been made to reduce disruption to nesting birds (i.e., minimizing handling time, checking burrows a second time each season only if there is evidence of the uncaptured partner incubating), some individuals likely have significantly lower tolerance to disturbance and are not recaptured again in the study area. Regardless of the cause, a dataset that includes both transients and non-transients violates the assumption of homogeneity of recapture probability in CMR models and results in biased estimates of survival (Lebreton *et al.* 1992). This can be overcome by (1) including a TSM effect in model sets for this species, with survival allowed to differ between the first year after marking and all subsequent years, regardless of whether goodness-of-fit tests show strong effects (e.g., this study); or (2) using a double-capture criterion, whereby individuals that were caught only once are presumed to be transients and are removed from capture histories used in analyses (e.g., Nur *et al.* 2019). However, the latter does not allow for reporting on the magnitude of the TSM effect.

Apparent survival estimates can underestimate true survival due to a lack of information on recaptures from outside the study area (Kendall *et al.* 2013), including movement of marked birds to burrows that are still in the colony but outside of the study plots. Based on our limited CMR time series, one quarter of the marked and recaptured birds in our study were encountered in more than one burrow within the study area, suggesting that burrow fidelity could influence estimates of apparent survival. However, the majority of the inter-burrow movements we observed were within short distances, either within the same study plot or to a neighbouring one; similar observations were made at Bon Portage Island, a colony 375 km southwest of Country Island, on the southwestern tip of Nova Scotia (Fife *et al.* 2015). Further, a long-term CMR study at Kent Island documented only a single instance of a breeding bird moving from one study plot to a non-contiguous plot in 40 years of monitoring over 12 000 nesting attempts (Pollet *et al.* 2021). Notably, many of the movements observed in our study were instances of an individual bird having been encountered in multiple burrows within a single season, perhaps during 'neighbourly visits,' given the social nature of this species (Stenhouse & Montevecchi 2000). Another factor to consider is the accessibility of a burrow to researchers. Burrows that are easily accessed (e.g., those with straight entrances and short depth) likely have higher recapture probability. Elongation of burrows over time can also occur, where birds continue to excavate burrows each breeding season, eventually reaching lengths whereby adults can be present in a burrow but are occasionally beyond the reach of field researchers. At some colonies where this has been a common issue, researchers in the past have created a hole at the apex of their reach to then use as an access point to reach further (e.g., Pollet & Shutler 2018). These holes are then covered over and used again in future checks as a 'trap door' access option. This method does, however, create additional disturbance to the burrow and has rarely been required at Country Island. Regardless, recording annual covariates that may influence recapture probability, such as the proportion of monitored burrows that were confidently checked or total field hours at each recapture occasion, could improve estimates of apparent survival rates, as estimates can be biased low if heterogeneity in recapture probability is not accounted for (Prévot-Juilliard *et al.* 1998).

Predators and burrow habitat

Standardized transect surveys for evidence of predation on storm petrels were conducted at Country Island in 2018 and 2019 (Hoeg *et al.* 2021). Evidence of predation was remarkably scarce in both years (only two carcasses found in 2018), although transect monitoring was conducted during the months of active predator deterrence and transects were limited to a small forested area near to the researcher field camp (Hoeg *et al.* 2021). In 2001–2008, similar predation surveys covered a larger area with a two-metre wide transect across the entire island; in these earlier years, an average of 27 individual remains were detected annually (JCR unpubl. data). At Bon Portage Island, no avian predator management occurs, and both American Herring and Great Black-backed gulls nest on the island. Transect surveys at this colony in 2018 and 2019 detected the remains of 46 adult storm petrels each year, leading to estimates of 4 000 individuals depredated per year and up to a 5% annual loss of adults (Hoeg *et al.* 2021). Earlier estimates of adult apparent survival at Bon Portage Island are low (0.78 ± 0.04 during 2009–2014), with some evidence that closer proximity to nesting gulls reduced survival (Fife *et al.* 2015). Overall, predation pressure has likely been lower at Country Island relative to other key colonies in Atlantic Canada due to predator control for the protection of Roseate Terns. Despite these activities, predation is still not negligible (Canadian Wildlife Service 2019, Hoeg *et al.* 2021).

Mean rates of apparent survival at Country Island were 0.06 lower within forest stands than in open areas with dense fern cover and were especially low in forested areas lacking understorey vegetation. One possible explanation is that storm petrels nesting in burrows within forested habitat were more vulnerable to predators; predators hunting within forest cover may be more likely to remain undetected by human stewards and have better visibility and access to storm petrels and their burrows in the absence of thick understorey vegetation. Transect surveys to detect predated birds over eight years (2001–2008) found that more than half of detected carcasses were in forested habitats (52%, with another 10% in fern/grass, 12.5% on the rocky shoreline, and the remainder in heath/shrub habitat; JCR unpubl. data). Further, in 2020 and 2021 when researchers were unable to maintain a continuous presence on the island through the tern breeding season, direct observations of ravens and crows was noted, along with evidence of digging around burrows in the storm petrel CMR plots, particularly within forested areas (RAR pers. obs.). Additionally, a minimum of 14 active American Herring Gull nests were found in open habitat in the centre of the island in 2021, and large groups of gulls were seen roosting in this same area (upwards of 300 individuals on one occasion in June). Thus, active predator management at Country Island since 1998 has likely been effective in reducing predator presence, but adult mortality from predation still occurs, particularly in forested areas.

Continued monitoring at this site will be critical in providing the necessary CMR data to refine estimates of annual survival and to understand the multi-faceted drivers of interannual variation in these rates. Direct monitoring of mustelid, corvid, and gull presence and efforts to detect evidence of predation in study plots would help determine where and how adults are being depredated. While monitoring transects have been used in the past to record evidence of storm petrel predation, this approach is limited in temporal and spatial coverage, and it can result in high disturbance and the potential destruction of fragile burrows. Assessment of regurgitated gull pellets around nests and roost sites may provide simple and direct evidence of gull predation rates, which could be monitored annually (Stenhouse & Montevecchi 1999, Steenweg *et al.* 2011, Mills 2016). An alternative approach may be to use remote time-lapse infrared trail cameras to detect the presence and activity of predators in representative habitat types throughout the entire breeding season (e.g., Wanless *et al.* 2012). This could also help to detect other direct sources of adult mortality, including periodic predation events by mustelids. For example, in 2015, a single American Mink *Neovison vison* killed ~1 000 adult storm petrels during the early breeding season; in 2017, a Northern River Otter *Lontra canadensis* dug up ~200 storm petrel burrows and killed at least 150 adults, although this occurred outside of the monitoring plots (JCR pers. obs.). Overall, standardized protocols for quantifying determinants of apparent survival probability (i.e., predation pressure, burrow habitat, emigration beyond monitored plots) and covariates of recapture probability (i.e., search effort and burrow accessibility) would improve future efforts to estimate annual survival rates at Country Island as well as at other breeding sites in the region, ultimately assisting in the development of population projection models for petrels in Atlantic Canada.

CONCLUSIONS

Because of predator management, the storm petrel colony at Country Island has experienced relatively low predation pressure compared to other breeding sites in Atlantic Canada. However, adult survival rates still appear depressed relative to storm petrel colonies in western Canada (Rennie *et al.* 2020) and relative to long-lived procellarids in general (Warham 1996, Hamer *et al.* 2001). The lowest adult survival rates occurred in forested habitats with open understory, where predation may have had the most influence on adult mortality. The Atlantic Canada storm petrel population as a whole is facing regional declines, driven at least in part by overall low adult survival (Robertson *et al.* 2006, Wilhelm *et al.* 2015, COSEWIC 2020). Many contributing factors are at play, both at breeding sites and in the offshore marine environments that the birds rely upon throughout the annual cycle. Different combinations of pressures are likely interacting to influence the processes depressing survival rates at each colony. Collaborative monitoring and integrated population modelling efforts are currently underway among many of the most significant breeding sites to identify means of mitigating low survival rates and encourage population recovery (COSEWIC 2020). This study is an important step in contributing to this broader conservation and management initiative.

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