



RESEARCH

Capturing the imminent extinction of a kakaruai/South Island robin population

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Abstract: The fragmentation of forested environments in Aotearoa | New Zealand has resulted in many small, geographically isolated populations that face an increased risk of extinction. However, population extinction itself, and its proximate causes, are rarely witnessed scientifically. As part of a broader study, we assessed the population status of a remnant kakaruai (South Island robin; *Petroica australis*) population within the Ōtepoti | Dunedin area. We compared parameters of this remnant population at Silver Stream (no recent predator control) with a translocated population at Orokonui Ecosanctuary (a fenced mainland ecosanctuary). Specifically, we indexed the abundance of mammalian predators and invertebrate biomass and monitored breeding behaviours and nesting outcomes in the spring and summer of 2022–2023. The Silver Stream population has now almost completely disappeared; we located a single female, resulting in a 10:1 male-biased sex ratio. We did not detect any difference in invertebrate biomass between Silver Stream and Orokonui, where the kakaruai population is thriving. Mean rat tracking was between 2% and 27% at Silver Stream, whereas only mice were detected at Orokonui. Rats have most likely contributed to the decline of the Silver Stream population as they target incubating females on nests. Our results emphasise that the decline of native forest birds is ongoing, and local extinction is imminent in the Silver Stream kakaruai population in the absence of predator management. Failure to prevent this local extinction may result in the loss of one of only two remaining populations of kakaruai on the east coast of Te Wai Pounamu | the South Island.

Keywords: food availability, fragmentation, local extinction, *Petroica australis*, population decline, predation, resource limitation, sex-ratio

Introduction

Island ecosystems are a focus for conservation efforts because they hold a disproportionate amount of global biodiversity (Kier et al. 2009) and face increased threats (Spatz et al. 2017). A great number of species in island ecosystems are highly threatened, while others have already gone extinct (Tereshy et al. 2015). Yet even species that are still common in island ecosystems are at risk and undergoing declines in abundance and distribution through local extinctions (Elliott et al. 2010; Paxton et al. 2016; Walker et al. 2019). Populations that are fragmented can experience local extinctions through changes in demographic rates due to deteriorating local environments (Hanski 1998; Miskelly & Sagar 2008), or by stochastic effects if populations are already small (Monks & O'Donnell 2017; Montie & Thomsen 2023). Local extinctions often go unnoticed. Despite the processes that drive populations to low numbers (ultimate causes, or the declining population paradigm) being generally known, the processes that deliver the coup de grâce are often less known (proximate causes or the small population paradigm; Caughley 1994; Duncan &

Blackburn 2007). However, it is important to understand both processes to better prevent further population fragmentation, range decline and extinction (Caughley 1994).

Like many oceanic islands, Aotearoa | New Zealand's (hereafter Aotearoa) avifauna is unique, having evolved in the absence of mammalian predators, and has already suffered high rates of extinctions. Indeed, 43.5% of terrestrial birds went extinct in mainland Aotearoa after human settlement (Wood 2023). In addition, 37% of native bird species are threatened (Robertson et al. 2021). Many extant bird species, and in particular forest birds, have become regionally scarce, with isolated local populations (Parlato et al. 2015; Walker et al. 2019). Even in common and widespread species, declines in abundance and distribution are ongoing (Elliott et al. 2010; Walker et al. 2019), but often go unnoticed.

While much of the initial decline in range of forest bird species is attributable to loss of forest habitat (reduction of native forest by 71%; Ewers et al. 2006), ongoing declines are likely due to predation by introduced mammals and further habitat degradation (Innes et al. 2010). Specific behavioural traits expose some bird species to higher rates of predation

by introduced mammals than others, including loss of flight or restricted ability to fly (Clout & Craig 1995), tameness (Muralidhar et al. 2019), and cavity-nesting (Greene & Fraser 1998). Predation may result in populations having low nest and adult survival (e.g. Armstrong et al. 2006a), resulting in a skewed sex ratio for species with female-only incubation (e.g. Greene & Fraser 1998). Individuals may also change their behaviour such as the choice of nest sites (Götmark et al., 1995). Limited food supply is a potential contributor to population declines, as all birds must invest time and energy to obtain sufficient nutrition (Boulton et al. 2008). Many of the mammalian predators in Aotearoa are omnivorous, not only preying on native birds directly but also consuming the same food resources (Clout et al. 1995). Few studies have examined the role of food supply for native bird populations (Innes et al. 2010), a large component of this being the difficulty in investigating this relationship in the overwhelming presence of invasive mammals. Comparison of remnant populations with nearby populations in ecosanctuaries (where introduced mammals are eradicated; Innes et al. 2019) can provide insights into processes affecting populations.

Here, we report the likely imminent extinction of a local kakaruai (South Island robin; *Petroica australis*) population that is located at the edge of the species' current range. The kakaruai is a small (35 g) insectivorous forest passerine, closely related to the toutouwai (North Island robin; *P. longipes*). Kakaruai become sexually mature in their first year and can live up to 15 years (Higgins et al. 2001). They form monogamous pairs and females solely incubate the 2–3 clutches. Kakaruai are a prime example of a once widespread species that now exists in fragmented small populations and, even within still forested areas, occupies less than 40% of its former range (Parlato et al. 2015). Only two small populations persist east of Kā Tiritiri-o-te-Moana | the Southern Alps, one in Kaikōura (Flack 1973; Gill 1980) and the other in Ōtepoti | Dunedin. The Ōtepoti | Dunedin population encompasses the Silver Peaks and Silver Stream populations and the translocated Orokonui Ecosanctuary population. Kakaruai are classified under the New Zealand Threat Classification System as At Risk: Declining (Robertson et al. 2021), while in Otago, the regional threat status of kakaruai is Regionally Vulnerable (Scott Jarvie, Otago Regional Council, pers. comm.).

We studied kakaruai in Silver Stream and Orokonui. Between 2010–2014, nest monitoring of 6–10 pairs at Silver Stream suggested relatively low nest survival, with annual estimates ranging between 2.7–10.4% compared with 64.3–73.0% nest survival at Orokonui (Appendix S1). In response to low kakaruai nest survival at Silver Stream in 2012, 50 rat traps were installed, remaining in place until 2015, although they were not operational in the 2014/15 summer season. After this point, the bait was changed to target stoats, and the traps were serviced for an additional two years (van Heezik et al., 2020). Since this time, no further predator control measures have been implemented. Nest monitoring of 11–15 pairs continued in Silver Stream from 2014–2017, but nest survival never exceeded 22.7% (Appendix S1). Adult survival between 2010–2014 ranged between 83.0–88.4% at Silver Stream compared with 85.4–90.1% at Orokonui (Jones 2016; Appendix S2). Interestingly, in comparison to toutouwai populations where female survival is lower compared to males in the presence of introduced ship rats (*Rattus rattus*; Armstrong et al. 2006a; Parlato & Armstrong 2012), Jones (2016) did not find differences in adult survival between sexes.

Our aims were to assess the environmental factors affecting

kakaruai populations and the current population status at Silver Stream compared to Orokonui. Specifically, we measured relative abundance of mammalian predators and availability of invertebrate biomass and carried out breeding surveys and nest monitoring of kakaruai at both sites.

Methods

Study sites

The 120-ha Silver Stream catchment is 9 km northwest of central Ōtepoti (45.8108° S, 170.4193° E) and is dominated by kānuka (*Kunzea robusta*; Parker 2013). Ship rats (*Rattus rattus*), mice (*Mus musculus*), brushtail possums (*Trichosurus vulpecula*), stoats (*Mustela erminea*), and feral cats (*Felis catus*) are present in the area and sporadic predator control measures have been implemented but are not routinely maintained (van Heezik et al. 2020). The kakaruai population at Silver Peaks is confined to a 100-ha mature Douglas fir (*Pseudotsuga menziesii*) and Monterey pine (*Pinus radiata*) plantation (Borkin 2007). The Silver Stream population is separated from the Silver Peaks population by the Silver Peaks Range, with no evidence of movement between them (Schadewinkel et al. 2014).

Orokonui Ecosanctuary (45.7618° S, 170.6069° E) is approximately 15 km northeast of Silver Stream. It encompasses 307 ha of land primarily characterised by secondary forest, mainly of kānuka and broadleaved species, and a few large developing podocarp species (Tanentzap & Lloyd 2017). The sanctuary has eradicated most introduced mammals, with the exception of mice, which are controlled. Kakaruai were initially reintroduced to Orokonui through two translocations from Silver Peaks and Silver Stream: the first in 2010, involving 25 individuals of mixed age and the second in 2011, involving 20 juveniles (Schadewinkel 2013).

Predator and invertebrate abundance

We indexed rodent (1-night survey using peanut butter bait) and mustelid (3-night survey using rabbit meat) abundance using standard tracking tunnel procedures (Gillies & Williams 2013). Six lines consisting of ten tunnels at 50-m spacing at each site were used for rodents and three lines consisting of five tunnels at 100-m spacing were used for mustelids at each site (Pearmain-Fenton 2023). Surveys were conducted during the peak nesting period of kakaruai in October, November, and December 2022. Prints were identified following Ratz (1997), with all rat prints assumed to be ship rats based on the species distributions described by Cunningham and Moors (1996).

Kakaruai feed primarily on the ground by visually searching for ground invertebrates in leaf litter (Powlesland 1981). We therefore indexed leaf litter invertebrate abundance using pitfall traps using standard techniques (Sherley & Stringer 2016). At both sites, we installed six grids, one at the centre of each tracking tunnel line. Each grid consisted of four traps arranged in a 5 × 5 m grid with an additional fifth trap in the centre of the square. The five traps were congregated as a single sampling unit. Pitfall traps were operated during the peak chick rearing period of kakaruai in October 2022 by checking traps daily for five continuous days (see Pearmain-Fenton 2023 for detailed invertebrate monitoring methods). After each day, all invertebrates were collected and immediately preserved in a 50% monopropylene glycol and 50% water solution. Contents were strained using a 200-micron mesh sieve, and

each sampling unit was flushed twice with water to remove residual preserving fluids and dried at 60 °C for 72 hours. The total dry weight of each unit was then recorded.

Kakaruai monitoring

At Silver Stream, all publicly accessible tracks were searched for the presence of kakaruai (3× per week, between 08:00 and 13:00). Male kakaruai territories were determined prior to their breeding season (August–January; Flack 1979) by walking transects and playing kakaruai calls every 200 m, followed by two minutes of observation (Duncan et al. 1999). Males were trained to approach observers for mealworms (*Tenebrio molitor*), enabling banding of individuals for future identification (Powlesland 1981). At Orokonui, we remained on public paths in the southernmost section of the ecosanctuary (35 ha). Audio callback was not necessary at this site as males were less timid towards observers. We ceased searching for territories after we had identified ten breeding males.

Nests of active breeding pairs were located by following females. We monitored each nest every 3–4 days by observation from a distance to detect nest activity. Nests were also inspected once per week using a waterproof endoscopic camera mounted to a 3 m extendable pole. The camera was placed above the nest (< 60 s in duration) so the contents and nesting stage could be determined, with these checks performed only when the females were distracted and away from the nest. Nesting pairs were observed from the first instance of nest building (when possible) until three weeks after fledging, when parents were still feeding juveniles. In addition, we recorded the tree species where the nest was built and the distance of the nest from the ground to account for site selection preferences between populations.

Statistical analyses

Data were analysed in R (ver. 4.2.1; R Core Team 2022). For tracking tunnel data, we created an index of relative abundance for ship rats and mice following Gillies and Williams (2013). For each species (ship rats and mice), this was expressed as the mean percentage of tunnels tracked per line. We compared invertebrate abundance (log-transformed combined dry weight of invertebrate biomass per grid) between sites using t-tests.

Nest success was defined as the percentage of nests that survived from initiation to completion, with at least one fledgling leaving the nest (Mayfield 1975). To correct for bias in finding nests at different stages of the nesting cycle, we calculated the daily survival rate (DSR) following Shaffer (2004). A logistic exposure model was created with the R package lme4 to calculate the DSR (Bates et al. 2015). Unlike the Mayfield estimate, the logistic exposure model requires no assumptions about when nest losses occur (Shaffer 2004). The initial logistic exposure model included breeding pair as a random effect (to account for the non-independence of repeat sampling and because parents build new nests for each subsequent breeding attempt). However, the variance of the random effect was inestimable. Therefore, the random effect was removed from the final model, as recommended by Matuschek et al. (2017). The nest survival rate (%) was then calculated using the DSR raised by the power of 39 (number of days in nesting period) following Mayfield (1975).

Literature review

We conducted a literature review to supplement data on vital rates of the Silver Stream and Orokonui kakaruai populations.

A comprehensive search was conducted through the University of Otago academic database and institutional repository to identify past theses and dissertations that utilised the Silver Stream and Orokonui kakaruai populations as study sites. A systematic search was performed within the journal *Notornis*, the *New Zealand Journal of Zoology*, and the *New Zealand Journal of Ecology* databases to supplement the data available in the theses. A combination of relevant keywords and related terms was used to ensure the retrieval of related literature. Terms included “Kakaruai”, “Toutouwai”, “South Island Robin”, “New Zealand Robin”, “Silver Stream”, “Orokonui”, and “fragmented landscape”. Boolean operators were employed to refine and expand the search queries. Studies deemed relevant to this review had to align with our criteria: they must reference either the Silver Stream or Orokonui kakaruai populations directly and must address at least one of the following: sex ratio, nest survival, nest site selection, adult survival, territory size.

Results

At Silver Stream, mice and ship rats were detected throughout the kakaruai breeding season (Fig. 1). The mean rat tracking rate ranged from 2% (October) to 27% (December) during the nesting period at Silver Stream. At Orokonui, only mouse prints were recorded (Fig. 1). The mouse tracking rate was higher at this site (72%) than at Silver Stream (35%) in December. Mustelid tracks were not detected in tunnels at either site. Invertebrate biomass was similar between sites, with a mean sampling unit biomass of 0.05 g (\pm 0.06 SE) at Orokonui and 0.08 g (\pm 0.03) at Silver Stream ($t=1.21$, $df=23$, $p=0.12$; Fig. 2).

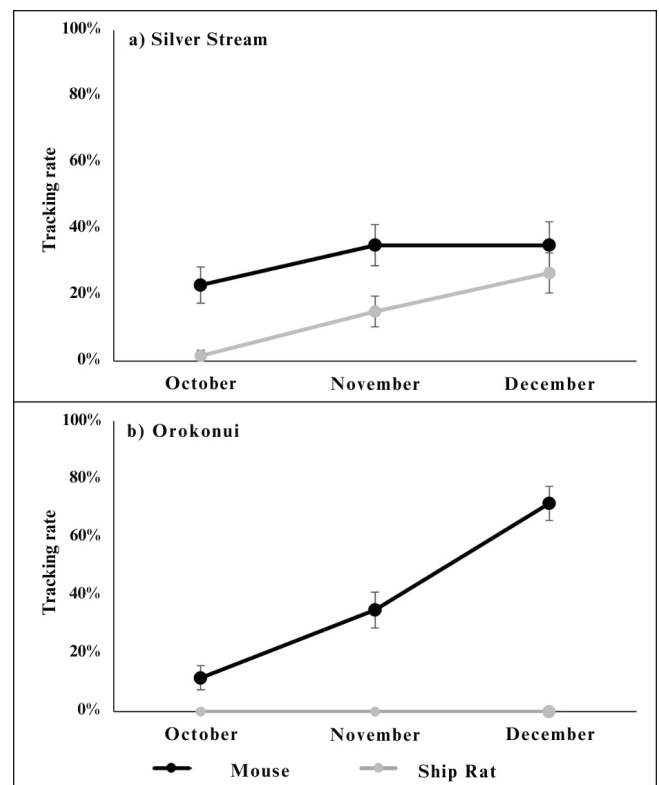


Figure 1. Mean rodent tracking rate (with standard error) from a) Silver Stream and b) Orokonui over three sampling rounds, October–December 2022.

Sex ratio

At Silver Stream, we identified only one breeding pair that persisted to the end of the 2022 season despite extensive search effort (an average of 4 h per day over 46 days, totalling 184 h). Ten male territories were located. We recorded an additional four (minimum) to eight (maximum) males at this site in less consistent locations over the breeding season, so their territories could not be located. In total, only two females were identified at this site. One was identified at the beginning of the breeding season (early August) but was never seen again. The male from this pair was continuously monitored but was not seen

displaying any behaviours indicative of active breeding and instead returned to behaviours associated with unpaired males (Fig. 3). This meant only one actively breeding pair could be monitored at this site for the 2022 season. The sex ratio for the Silver Stream population was therefore 10:1, excluding the female who did not survive to the end of the 2022 season.

At Orokonui, ten breeding pairs were located within the 35-ha sample area at the southernmost section of the ecosanctuary. Many of these territories overlapped, with some nests located < 50 m from neighbouring pairs. We did not identify any male kakaruaui that were not paired with a female by the end of the breeding season. Although we did not cover the entire Orokonui population, the sex ratio of the observed sample population was 1:1.

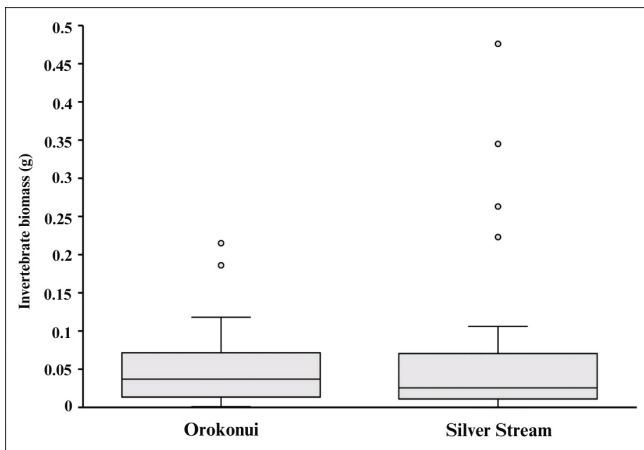


Figure 2. Mean invertebrate biomass at Orokonui and Silver Stream, November 2022. Each sampling unit consisted of five individual pitfall traps. Each site contained six sampling units. Dry weight (g) was summed from four consecutive nights of pitfall trapping.

Nesting success and nest site selection

At Silver Stream, a single pair produced two clutches. The first failed due to predation, and the second successfully fledged three young. Both nests were constructed inside kānuka, positioned high in the tree canopy, and placed on the host species' outermost branch. DSR for this site could not be calculated as the sample size was too small.

At Orokonui, ten pairs were monitored over 14 nesting attempts, with an estimated nest survival rate of 31.5% ($\pm < 0.001\%$ SE). The maximum number of clutches was three, with a mean of 1.47 clutches. Five of the nests monitored (with all of these being the first clutch attempt for each pair) failed due to a severe weather event, where unusually heavy snowfall and low temperatures caused many of the nests to be abandoned by their parents. On 6–7 October, the average daily temperature was 1 °C compared to the 10 °C average over October 2022 (National Institute of Water and Atmospheric Research 2023).

The most frequently selected nest host species was kānuka

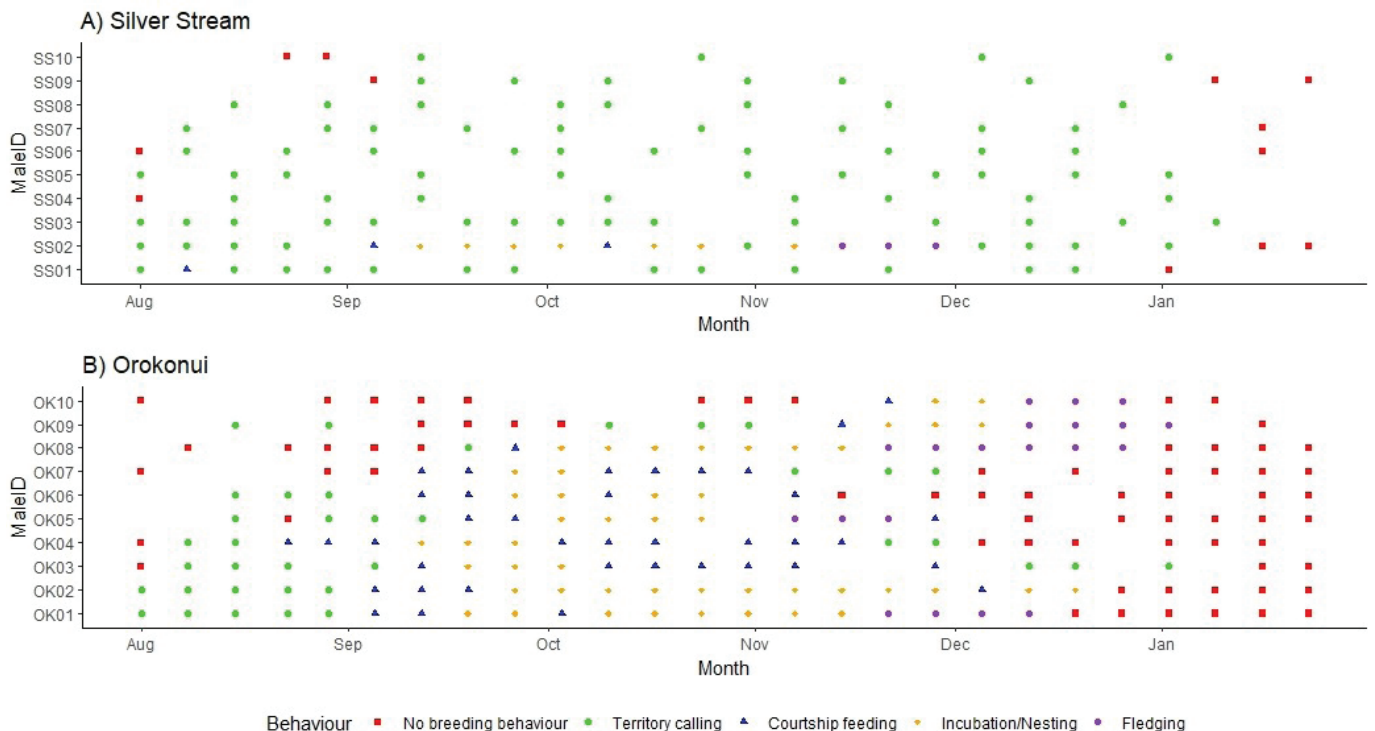


Figure 3. Comparison of breeding behaviours from 20 male kakaruaui (*Petroica australis*) at a) Silver Stream and b) Orokonui over the 2022–23 breeding season.

(42.8% of all nests), followed by silver fern (*Cyathea dealbata*; 28.6%). Nests were recorded at a mean height of 2.63 m above ground, with the highest being 10 m and the lowest being 1 m above ground. 100% of the Orokonui nests were located within the innermost branch or trunk of the host species.

Literature review

Table 1 collates all the information from the literature review on kakaruai vital rates for the Silver Stream and Orokonui populations. Although estimated nest survival at Silver Stream fluctuated significantly between years (and across different intensities of predator control, as explored further in the discussion), the mean survival rate across all years was significantly lower than that of Orokonui (12.57% compared to 71.59%). Juvenile recruitment and adult survival rates between the two sites also reflect this disparity (Table 1). Although sample sizes at Silver Stream were small, evidence from the literature confirms a stark difference in nest site preferences between the two populations.

Discussion

Our study highlights that even relatively common native species in Aotearoa are still at risk of local extinction and further fragmentation throughout their formerly widespread range. The small local population of kakaruai at Silver Stream has a severely male-biased sex ratio, likely due to on-going predation pressure on incubating females. There was no difference in invertebrate biomass between Silver Stream and Orokonui, where the kakaruai population appears to be expanding (Pearmain-Fenton 2023), suggesting that poor food availability has not caused the population decline at Silver Stream. Local extinction of the population at Silver Stream is highly likely, unless predator management is implemented with urgency.

Differential survival of females and males in the presence of introduced predators has been demonstrated in various forest bird species in Aotearoa and has resulted in male-biased sex ratios. Female toutouwai had lower survival compared to males, and female survival decreased with rat tracking rates (Armstrong et al. 2006b). A 3:1 male sex bias due to predation

of females on the nest has been detected in kākā (*Nestor meridionalis*) populations (Greene & Fraser 1998, Greene et al. 2023). Male-male pair bonds have been observed in North Island kōkako (*Callaeas wilsoni*; Innes et al. 1996). The decline in distribution of species such as kōkako was delayed due to the longevity of individuals, but was rapid once only small isolated and fragmented populations existed (O'Donnell 1984; Innes & Flux 1999). As dispersal is sex biased towards females in birds (Greenwood 1980), the extinction vortex for small, isolated populations may be particularly severe if female survival and recruitment is low.

Past population survey data suggest a trend of population decline over time among the Silver Stream kakaruai, starting from the first standardised survey in 1998 (Appendix S3). Prior research showed that nest survival was poor, but adult survival did not differ between sexes at Silver Stream (Table 1). While there was also no difference between male and female adult survival of kakaruai in beech forest in the Marlborough Sounds, kakaruai adult and nest survival declined with increased rat tracking rates (Bell et al. 2021). Although the observed sex bias in the Silver Stream population is likely a result of prolonged predator pressure, we are unable to confirm how this skewed sex ratio emerged despite no discernible difference in survival rates between male and female kakaruai based on available data.

Food availability can influence nest survival as has been shown for toutouwai, where nest survival rates increased with invertebrate biomass (Boulton et al. 2008). In concordance with other studies, we found no significant difference in invertebrate biomass between Orokonui and Silver Stream (Watts et al. 2014; Vergara et al. 2021). There are two reasons why invertebrate abundance may be similar between sites. First, both native and non-native insectivorous birds are likely to exert predation pressure on invertebrates on both sides of ecosanctuary fences to different degrees (Vergara et al. 2021). Second, increased predation of invertebrates by mice inside fenced sanctuaries may also obscure any potential differences in food availability for kakaruai. Mice have been implicated in the decline of many invertebrate populations in Aotearoa, with litter-dwelling species at particular risk (Watts et al. 2022). Experimental food supplementation could further clarify the role of food availability in the wider decline of kakaruai.

Table 1. The observed outcome for Silver Stream and Orokonui kakaruai (*Petroica australis*) populations over the 2022–23 breeding season. All literature cited is based on the Silver Stream or Orokonui populations.

	Kakaruai population at Silver Stream	Kakaruai population at Orokonui
<i>Sex ratio</i>	Male biased sex ratio of 1:10 (this study). All other males carry unpaired breeding behaviours for the entire nesting season (Fig. 3).	No sex bias was observed (this study). The sampled population had a sex ratio of 1:1. All observed females were paired.
<i>Nest survival</i>	Low, as mean estimated nest survival ¹ was 12.57% (from 2010–2016; Jones 2016; Appendix S1).	High, as mean nest survival was 71.59% (2010–2014; Jones 2016; van Heezik et al. 2020; Appendix S1).
<i>Nest site selection</i>	Nests are built high in the canopy, on the edge of branches far from the tree trunk (this study; Muralidhar 2017).	Nests are constructed low in the canopy and often in exposed areas (this study; Muralidhar 2017).
<i>Adult survival</i>	High, as mean adult survival was 85.67% (2009–2014; Jones 2016; Appendix S2).	High, as mean adult survival was 87.85% (2010–2013; Jones 2016; Appendix S2).
<i>Territory size</i>	Large (this study)	Small (this study and Pickerell 2020; < 1 ha).

¹Survival constituted any instance of recapture or any instance where a bird was clearly sighted and identified. Capture history data includes birds that originated from within the area as well as birds that arrived from or that moved to adjacent areas.

Conclusion

The Silver Stream kakarua population has a strong bias in sex ratio likely due to increased predation pressure on females and is now very close to local extinction. In comparison, the population at Orokonui is thriving (Pearmain-Fenton 2023; Table 1). Consistent predator control has shown positive responses in kakarua demographic rates (van Heezik et al. 2020; Bell et al. 2021), and has also resulted in populations returning to more even sex ratios in other native forest bird species (Greene et al., 2023). Predator control was implemented sporadically at Silver Stream prior to 2016. The site is just outside of the boundary where control of possums and stoats occurs as part of the Predator Free Dunedin project, one of 17 Predator Free 2050 landscape projects implemented since 2018 (Predator Free 2050 Limited 2023); it is also included in expansion plans. If predator suppression is immediately initiated at Silver Stream, it is still possible that this remnant population will survive. However, without intervention, the loss of this population could further diminish the already fragmented distribution of kakarua, highlighting the broader challenge of preserving small, isolated populations in the face of increasing environmental pressures.

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Data and code availability: the data and code used in this paper can be accessed by contacting the corresponding author.

Ethics: all fieldwork was conducted under the University of Otago Animal Ethics Committee (AUP-22-39). This project was also completed with permissions from the Ngāi Tahu Research Consultation Committee.

Conflicts of interest: the authors declare no conflicts of interest.

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Supplementary Material

Additional supporting information may be found in the online version of this article:

Appendix S1. Silver Stream and Orokonui kakaruai (*Petroica australis*) nest survival data.

Appendix S2. Silver Stream and Orokonui kakaruai (*Petroica australis*) adult survival data.

Appendix S3. Literature review of historic studies and population surveys of kakaruai (*Petroica australis*) at Silver Stream.

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