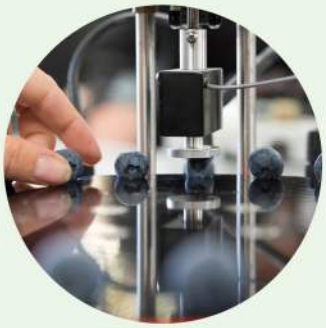







PFR SPTS No. 27343

# Interaction of spotted shags with northern North Island set net fisheries

*Prepared for Department of Conservation, CSP project INT2024-06*

Jingjing Zhang, Matt J. Rayner

June 2025

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Department of Conservation
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**KEYWORDS: Spotted shags, kawau tikitiki,set-net fisheries, at-sea behaviour, diving data, space-use, spatial overlap**



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# Contents

# Executive summary

## INT2024-06 Interaction of spotted shags with northern North Island set net fisheries

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June 2025

This research investigated the degree of spatial and temporal overlap between tracked kawau tikitiki and commercial set net fisheries in the Firth of Thames region. Previously, data of spatially explicit kawau tikitiki diving (foraging) events are available and ready use. Fisheries set net data were obtained from the Ministry for Primary Industries (MPI). We first explored the at-sea behaviour and range of kawau tikitiki, including diving frequency, diving depth and length of dive during the day, and between months. The locations of both kawau tikitiki diving and commercial set net activity were summarised by time of day, month and season, which reflected variation of foraging patterns over different life stages of kawau tikitiki throughout the year. Distinct diving behaviours were observed between male and female individuals and whether the birds foraged in marine farms. Probability density surfaces were calculated from these monthly and seasonal data, and hotspots of kawau tikitiki foraging and fisheries activities were identified. The degree of overlap between kawau tikitiki and fisheries activity-hotspots were estimated to approximate the likelihood of interactions. Fine-scaled behaviour patterns of the kawau tikitiki were assessed, and the spatio-temporal interaction events were also identified. The results of this analysis provided insights into the space-use patterns of kawau tikitiki with seasonal shifts in foraging distribution, including use of mussel farms and a pronounced spring concentration on the Thames coastline. The spatial overlaps between core foraging areas and set net operations were strongest during the spring. The spatial and spatiotemporal overlaps between foraging behaviour and fishing activity presents a conservation concern for this declining, and genetically distinct seabird population, that should be considered for fisheries management, such as restricting fishing areas during spring, and/or limiting fishing hours in the region.

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# 1 Introduction

The kawau tikitiki (spotted shag, *Phalacrocorax punctatus*) historically bred widely in the Auckland region, yet this species experienced massive population decline in the early 20th century because of unrestricted hunting. Shooting was banned in the 1930s and by 1960 populations had rebounded to at least 2000 breeding pairs in the Firth of Thames area. However, despite decades of legal protection and successful eradication of introduced predators from breeding colonies, numbers have continued to decline, pointing to threats occurring away from nest sites, particularly within the birds' foraging range (Woolly et al. 2024). In the last three decades populations in the northern North Island have been in steep decline, with fewer than 300 breeding pairs remaining (Robertson et al. 2021). These birds are now largely confined to a single breeding stronghold at Tarahiki Island in the Firth of Thames and a few smaller sub-colonies on Waiheke Island (Rawlence et al. 2019). Genetically distinct and regionally threatened, this population has been identified as a taxon of concern under the National Plan of Action – Seabirds 2020 due to its restricted range and alarming population trajectory, with the breeding colonies continuing to decline by approximately 2–5 breeding nests per year. Despite this, annual chick production remains high which suggests at-sea threats may be of major concern. Shags are known to be susceptible to bycatch in set nets and the coastal foraging range of these birds overlaps with set net fishing effort, suggesting the observed decline in numbers may be, at least in part, caused by fisheries related mortalities.

Recent collaborative research led by the Auckland Museum and Oregon State University has used GPS and dive-depth loggers to track the fine-scale movements of kawau tikitiki year-round (Orben et al. 2025) These data reveal consistent use of nearshore coastal habitats, including mussel farms and estuarine river mouths in the Firth of Thames. Critically, this foraging behaviour likely brings the birds into close and recurrent contact with commercial set net fisheries operating in the same areas. In 2023, two of 14 tracked birds died in what were most likely set net drownings off the Thames Coast (Matt J. Rayner unpublished data). Such incidents represent a significant threat to the ongoing survival of kawau tikitiki in the Hauraki Gulf.

This project (INT2024-06), commissioned by the Department of Conservation (DOC) through the Conservation Services Programme, builds upon that foundational tracking work. Its primary objective was to quantify spatial and temporal overlap between shag foraging behaviour and set net fishing effort. Using spatially explicit tracking and fisheries data, the project aimed to identify high-risk zones and times of year for bycatch, to inform targeted outreach and management responses. Outputs will support DOC's ongoing risk assessment processes and contribute directly to mitigating one of the most urgent threats facing this iconic seabird in the Hauraki Gulf.

# 2 Methods

Data used in this project have been previously collected as part of a collaboration between Auckland Museum and Oregon State University. In brief, we deployed GPS-temperature loggers on kawau tikitiki by capturing birds using a net gun at their breeding colony on Tarahiki Island and at a nearby mussel farm where they regularly forage. Each tag was mounted using a custom-made Teflon backpack harness incorporating a rustable weak link, designed to corrode in seawater over time and safely detach the device from the bird.

We collaborated with the biologging company Ornitela (Vilnius, Lithuania) to deploy solar powered GPS loggers weighing 26 g, well below the 3% body mass threshold recommended for seabird tracking. Tag programming was optimised to trigger a GPS fix each time the bird resurfaced from a dive, defined as crossing a 1 m depth threshold. This allowed for high-resolution tracking of foraging behaviour. Data were transmitted over 4G networks at set intervals, enabling the transfer of large datasets remotely.

## 2.1 Dive data

The analysis was based on dive data collected from GPS tracking devices attached to kawau tikitiki individuals from January 2023 to March 2024.

The dataset includes 256,452 dive records from 14 individual birds (Figure 1). Ten of the birds were randomly caught at the major breeding colony, and the other four at a mussel farm nearby. Each record contains information about dive depth (minimum, maximum, and mean), dive duration, and whether the dive occurred near a marine farm. Individuals are also identified by sex (male, female, or unknown) by Infogene New Zealand (InfogeneNZ).

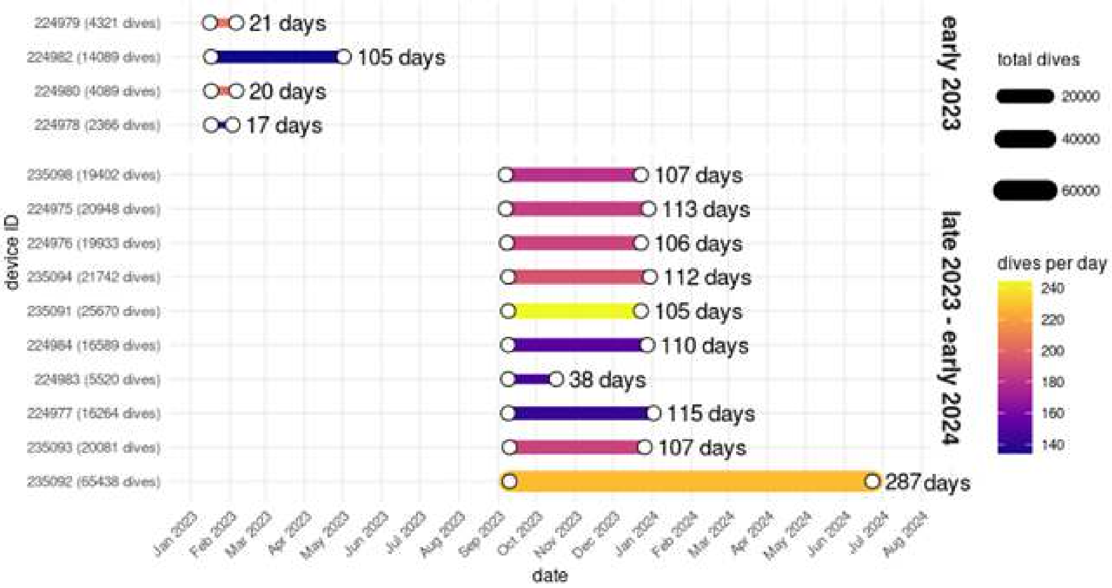



**Figure 1** Tracking duration and numbers of observations for each GPS device deployed on kawau tikitiki individuals.

## 2.2 Fisheries data and marine farms

The fisheries data were acquired from MPI based on a data sharing agreement between DOC and MPI. The time range of the fisheries data was 8 January 2020 until 24 March 2024, and contains 9169 rows of data, with each row consisting a set net fishing event that contains information of event ID, start date and time, and coordinates of the starting and ending locations of the fishing event. We also acquired the spatial polygon of the marine farms in the Firth of Thames.

## 2.3 Diving pattern analysis

We first explored the temporal coverage of our tracking data by summarising the tracking period of all studied individuals. This helped us to interpret the results and identify potential biases in our dataset. To understand the daily diving behaviour of the kawau tikitiki, we calculated the mean and standard error of the diving patterns, including dive depth, dive duration, and dive per day per bird. We plotted the diving patterns between 2023 and 2024, whether the kawau tikitiki were on marine farms, and between male and female individuals. The diving data are not balanced in terms of numbers of bird tracked as in different sex group and period of tracking due to the logistics and nature of the remote tracking studies of seabirds. We applied mixed-effects models to account for the hierarchical structure of the data, where multiple dive observations were recorded from the same individuals (i.e., pseudoreplication), using Linear mixed model and generalised linear mixed-effect model using lmer function of package lme4 (Bates et al. 2015) and glmer function in package glmmTMB (Brooks et al. 2017) in R (R Core Team 2024), and the post-hoc comparison was done with emmeans function in package emmeans (Lenth 2017).

To better understand the drivers of diving behaviour, we used mixed-effects models to analyse how dive depth, duration, and frequency were influenced by temporal factors (month), spatial factors (presence of marine farms), and individual characteristics (sex), while accounting for individual variation as the random effect. We also accessed the individual variances and residual variances using Intraclass Correlation Coefficient (ICC) that quantifies the proportion of total variance attributable to differences between individuals.

We further investigated the distribution of diving activity throughout the day, looking specifically at dive frequency, depth and duration hourly which provided insights into the foraging strategy of kawau tikitiki. Both monthly and daily diving patterns were used to analyse spatial and temporal interactions of kawau tikitiki and the set net fisheries.

## 2.4 Overlap of kawau tikitiki and set net fisheries

The fisheries data in the Firth of Thames from MPI were acquired by request made under the data sharing memorandum of understanding that DOC has with MPI. For the fisheries data, we first generated polygons as lines between the start and end locations per fishing event, and removed any record that had a polygon length more than 1 km long, or a part of the polygon was on land. As kawau tikitiki are visual foragers and their at-sea behaviours occur during the day, we also considered the temporal overlap between the fishing events and diving activities, and removed any fishing record/polygon in hours that had no diving activities recorded. The remaining fishing event polygons were then used in the sequential spatial overlap analysis between bird and fishing activities.

To understand the space-use patterns of kawau tikitiki within the Waitemata Harbour and Firth of Thames, we constructed overall and monthly spatial utility density surfaces (kernel density surface) of the kawau tikitiki with default reference bandwidth (href) and a grid size of 200 from the kernelUD function from the package (adehabitatHR) (Calenge 2011) to get more detailed contours over the tracking period. The contours of, and area of, the 95%, 50%, and 10% utilisation distributions were also drawn to mark the home range, core foraging areas, and highest-used areas, respectively. The fishing events fall inside of each contour range, and the percentage of these events in all fishing records were calculated, both for the overall tracking period, and per month.

At a finer spatiotemporal scale, we wanted to identify direct interactions between birds and fishing vessels from the current datasets based on spatiotemporal proximity. We defined a potential interaction as an instance where a bird and fishing event were within a specified distance threshold during the same time period. This analysis helps identify specific direct interaction events of concern rather than just general overlapping areas. We identified all interaction events within 300 m between the diving records and the fishing events that occurred concurrently. We categorised these events by every 50 meters and calculated the percentages that accounted for all interactions identified. The distribution of the interactions during a day were also plotted with the diving depth. All statistical analyses were conducted in R, and unless otherwise stated, values are presented as mean ± standard error (SE).

# 3 Results

## 3.1 Diving behaviour of kawau tikitiki

### 3.1.1 Temporal patterns between 2023 and 2024 study years

To study the dive patterns, the dive data set were summarised on three key metrics: 1. mean dive depth 2. mean dive duration 3. dives per bird per day. The error bar represented ±1SE of the mean values. Figure 2 shows the spatial distribution of all the dive records, day roosts, overnight roosts and mussel farms in the study area.

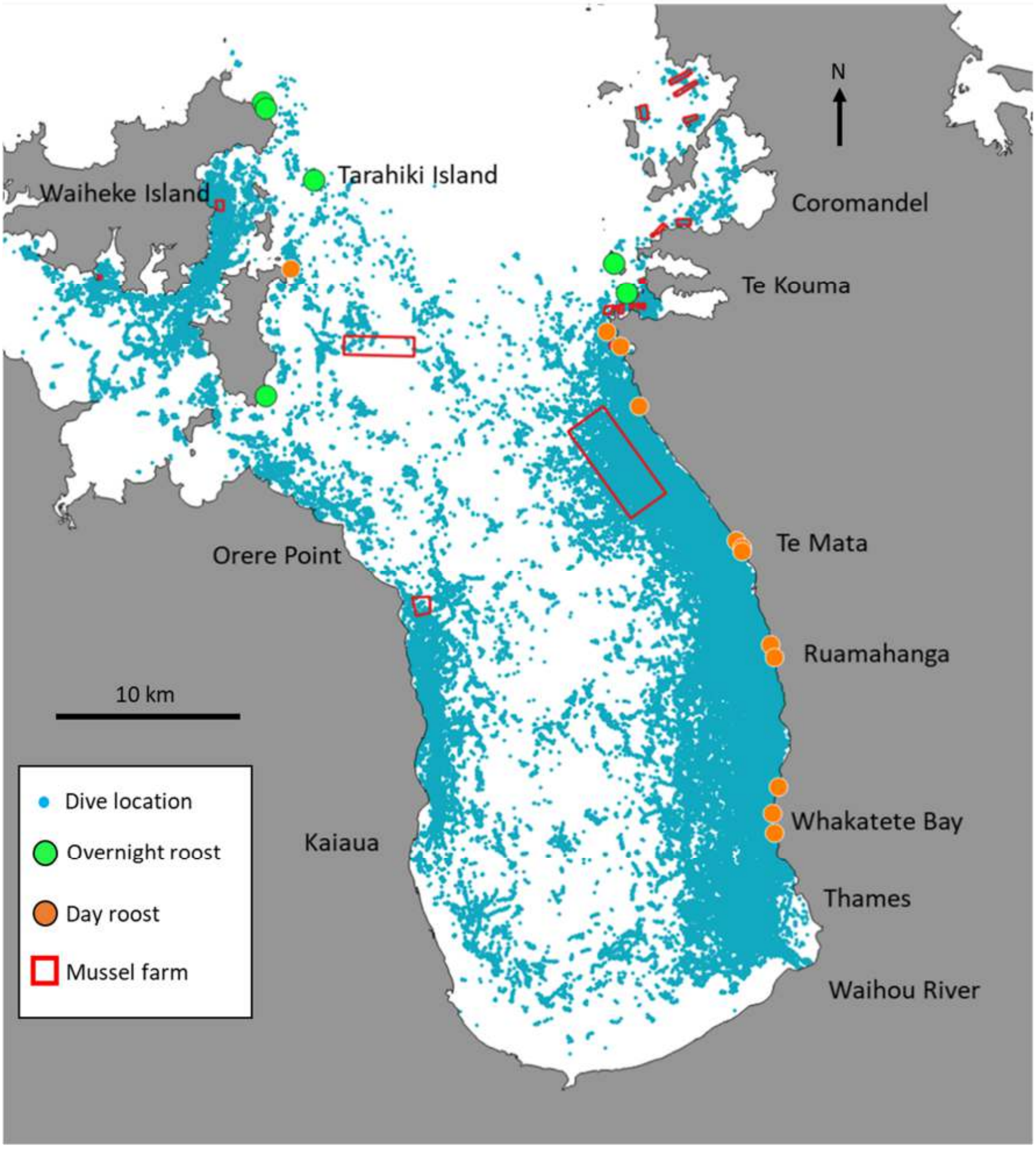



**Figure 2.** Spatial distribution of all dive records, day roosts, overnight roosts and mussel farms in the study area. Main breeding colony on Tarahiki Island also shown.

Mean dive depths generally ranged between 2–4 m, with seasonal variations (Figure 3). The deepest dives tended to occur during May–June (4.12 ± 1.30 and 4.28 ± 1.11 m). The average dive duration followed a similar pattern to dive depth, with longer dives corresponding to deeper dives. This suggests a consistent diving behaviour where birds spent more time underwater when diving deeper in winter compared to spring and summer. The number of dives per bird per day showed considerable variation throughout the year and between years, with more dives during the spring and summer months (September to February) compared to May and June.

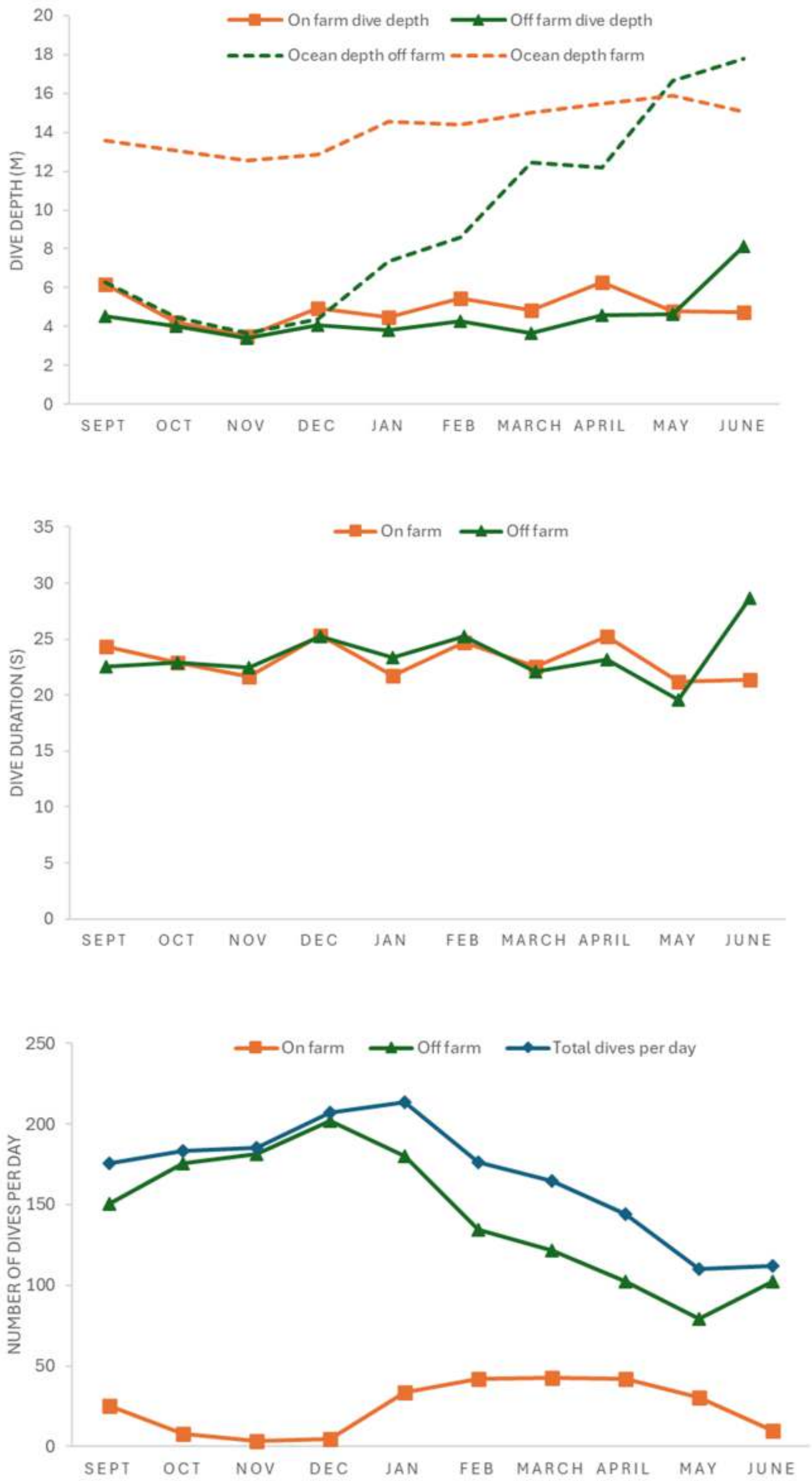



**Figure 3:** Dive patterns of kawau tikitiki (*Phalacrocorax varius*) during the 2023 and 2024 study years. The orange line shows on-farm diving behaviours, while the green line shows off-farm behaviour. The blue line shows total dives per day. From top to bottom: Mean diving depth of the birds over the tracking period along with mean ocean dive depths; mean dive duration; and mean number of dives per day.

The data overlapped from January to May of 2023 and 2024, and the comparison between years are based on this overlapping window between January and May. The mean total dive was lower in 2023 (2486.50 ± 910.10) compared to 2024 (3275.20 ± 761.24), with deeper dives (4.12 ± 0.53 m in 2023, 2.92 ± 0.12 m in 2024), and longer dive duration (26.53 ± 1.86 seconds in 2023, 21.12 ± 0.31 seconds in 2024) on average. Similar patterns were also observed in the mean dives per bird per day, with spotted shags tracked in 2023 preforming fewer dives per day, with 26.53 ± 1.87 times in 2023 and 21.12 ± 0.31 in 2024 between January to May.

### 3.1.2 Effects of marine farm

The kawau tikitiki displayed different dive behaviour when foraging near marine farms compared to natural areas (Figure 3). The kawau tikitiki had a higher chance of foraging near marine farms during autumn and winter, with between 23.78–28.99% of dives occurring on the marine farms from February to May. Compared to spring and summer, only 2.01–4,19 % of dives occurred near the marine farms in October, November and December during the tracking period.

While on farm, the birds dived deeper (3.76 ± 0.38 m) and longer (24.26 ± 1.32 seconds) compared to when they foraged at the other areas (3.17 ± 0.19 m in dive depth and 23.33 ± 0.82 seconds in dive duration).

### 3.1.3 Differences in diving behaviour of male and female

We also examined whether male and female (and unknown) kawau tikitiki exhibited different diving behaviours by comparing the mean, max and minimum diving depth, and dive duration (Figure 4).

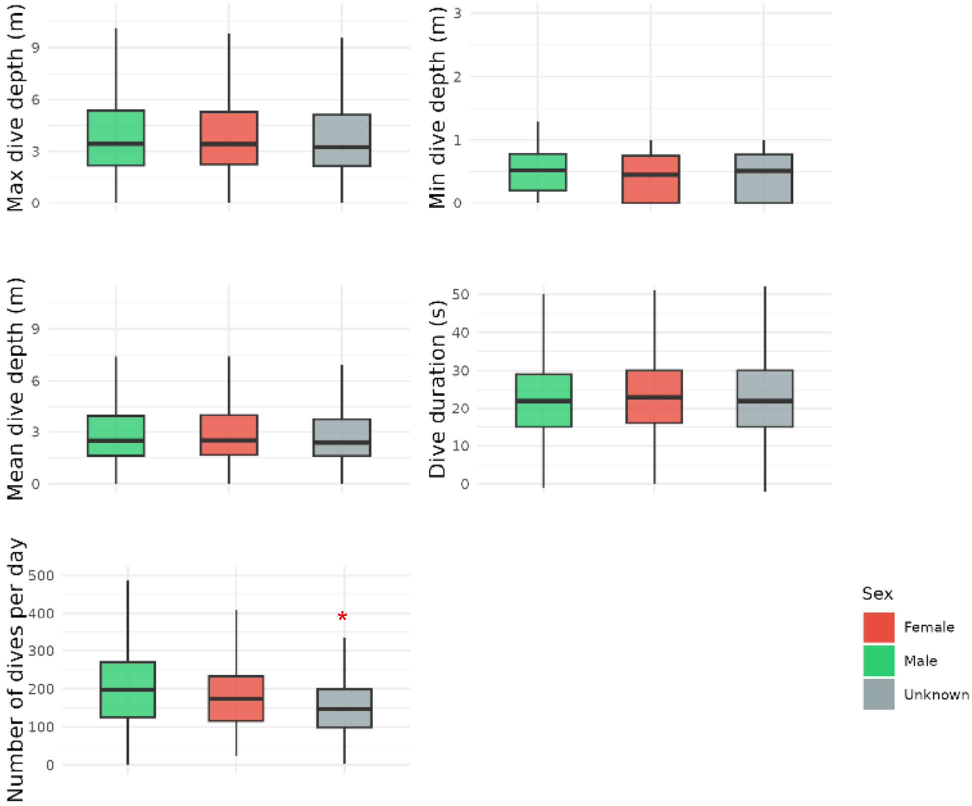



**Figure 4.** Diving patterns of male, female and unknown kawau tikitiki individuals. Parameters that show statistically significant from the mixed-effect models differences ($p$ < 0.05) are marked with an asterisk (*).

A series of linear mixed-effects models (LMMs) were used to test for sex differences in dive metrics, with individual bird included as a random effect. For dive depth metrics, males dived deeper on average than female (male: 4.14 ± 0.0076 m; female: 4.08 ± 0.010 m; unknown: 4.15 ± 0.013 m, with no significant differences among sexes (all pairwise contrasts F = 0.012, p = 0.99). Similarly, minimum and mean dive depths showed negligible variation: predicted means were 0.46 ± 0.018, 0.44 ± 0.021, and 0.49 ± 0.018 m for males, females, and unknowns respectively, with all comparisons non-significant (F = 1.55, p = 0.26). Mean dive depth was nearly identical across sexes (male: 3.06 ± 0.0055 m; female: 3.07 ± 0.0075 m; unknown: 3.05 ± 0.0093 m), with no evidence of group differences (F < 0.001, p = 1.00).

Observed dive durations were slightly longer in females (24.06 ± 0.047 s) and unknown-sex birds (23.85 ± 0.055 s) than males (22.88 ± 0.034 s). However, the modelled differences were not statistically significant (F < 0.001, p = 1.00).

On average, males preformed more dives (208.08 ± 4.39) than females (181.46 ± 4.55) and unknown individuals (155.01 ± 4.13 seconds). To evaluate differences in number of dives per day across sexes while accounting for repeated measures, we initially fitted a Poisson generalised linear mixed model (GLMM) with bird ID as a random intercept. However, model diagnostics revealed severe overdispersion (overdispersion ratio = 45.88), indicating that the Poisson assumption of equal mean and variance was violated. To address this, we refitted the model using a negative binomial GLMM, which introduced an additional dispersion parameter to account for variability beyond the Poisson expectation. The model estimated that males performed 198.36 ± 13.38 dives per day (95% CI: 173.80–226.38), while females and unknown individuals averaged 175.85 ± 13.27 (95% CI: 151.67–203.88) and 156.30 ± 11.14 dives (95% CI: 135.91–179.74), respectively. Unknown-sex individuals performed significantly fewer dives than males ($\beta = -0.24 \pm 0.10$, $z = -2.43$, $p = 0.040$), corresponding to an estimated 21% reduction in dive frequency ($\exp(-0.24) \approx 0.79$). No significant difference was detected between males and females ($\beta = -0.12 \pm 0.10$, $z = -1.19$, $p = 0.459$), nor between females and unknown individuals ($\beta = -0.12 \pm 0.10$, $z = -1.14$, $p = 0.493$). The model retained a small random effect for bird ID ($\sigma = 0.14$), and the estimated dispersion parameter ($\theta = 3.41$) confirmed suitability of the negative binomial structure.

### 3.1.4 Mixed-effects models

To evaluate how dive behaviour varied by month, marine farm presence, and sex, we applied linear and generalised linear mixed-effects models with individual bird as a random effect. The results revealed substantial imbalance in the number of individuals and observations across factor combinations, particularly for sex and farm status, with some groups dominated by unknown-sex individuals.

In the model for mean dive depth, both month and farm presence were highly significant predictors ($F_{1,214361}$= 180.9, $p < 0.001$; $F_{1,256444}$= 1460.0, $p < 0.001$, respectively), while sex had no significant effect ($F_{2,11} = 0.03$, $p = 0.97$). Dive depths were deeper within farms. In contrast, the model for dive duration varies between months ($F_{1,209109} = 235.2$, $p < 0.001$), but neither farm presence ($F_{1,256445} = 0.37$, $p = 0.54$) nor sex ($F_{2,11}$= 0.54, $p = 0.60$) explained significant variation.

A Poisson generalised linear mixed model (GLMM) was used to evaluate the effects of month, farm location, and sex on individual birds' daily dive counts, while accounting for repeated measures with a random intercept for individuals. The model revealed strong effects of both month and farm location: dive frequency increased slightly but significantly with month ($\beta = 0.033 \pm 0.0009$, $p < 0.001$), indicating a seasonal pattern, and birds off-farm were estimated to perform over four times as many dives per day compared to when on farm ($\beta = 1.46 \pm 0.007$, $p < 0.001$; $\exp(1.46) \approx 4.3$).

By contrast, sex was not a significant predictor of dive frequency. Females were estimated to dive about 17% less frequently than males ($\beta = -0.19 \pm 0.12$, $p = 0.118$; $\exp(-0.19) \approx 0.83$), and unknown-sex individuals about 14% less ($\beta = -0.15 \pm 0.12$, $p = 0.212$; $\exp(-0.15) \approx 0.86$), but neither difference reached statistical significance. The estimated random effect for individual was small ($\sigma = 0.18$), indicating modest between-individual variation in daily dive counts.

All fixed-effect coefficients are on the log scale due to the Poisson link function, and were exponentiated here for interpretation on the original response scale. For mean dive depth, the individual-level variance was 0.163 and the residual variance was 4.053, resulting in an Intraclass Correlation Coefficient (ICC) of 0.039. Similarly, the model for dive duration yielded an individual variance of 5.696 and a residual variance of 152.172, corresponding to an ICC of 0.036. For mean dive depth, the individual-level variance was 0.163 and the residual variance was 4.053, resulting in an ICC of 0.039. Similarly, the model for dive duration yielded an individual variance of 5.696 and a residual variance of 152.172, corresponding to an ICC of 0.036.

### 3.1.5 Daily diving patterns

As shown in Table 1, and as expected for this diurnally foraging species, the diving records of kawau tikitiki were concentrated during the day, and no record was found between 11pm to 3am. Most of the diving events occurred between 5 a.m. – 7 p.m., and concentrated during the hours with daylight. The birds dived deeper during the morning between 5 a.m. to 8 a.m., as well as later afternoon between 4 p.m. to 7 p.m., as can be seen in Figure 5.

Both males and females were primarily active during daylight hours. Males consistently made more dives than females throughout the day on average. The dive durations closely followed the pattern of dive depths, with longer dives corresponding to deeper dives. This maintained a consistent descent and ascent rate throughout the day.

## 3.2 Overlap of kawau tikitiki and set-net fisheries

### 3.2.1 Screening of fisheries data

Fisheries data were filtered to remove any records with geographic coordinates located on land from further analysis. This screening resulted in 736 records being removed for further analysis, which constituted 27.79 % of original 2648 records, and the filtered data had 1912 fishing records.

We added a hypothetical temporal end to the fishing record as 2 h after the starting time. This was based on the fishing practices for estimation of spatiotemporal overlaps between fishing events and diving events.

**Table 1.** Summary of diving of kawau tikitiki during the day by hours.

| hour of the day | no. of total recorded dives | no. of bird tracked | no. dive per bird per day in the hour | mean dive depth (m) | mean dive duration (s) |
|---|---|---|---|---|---|
| 3 | 11 | 2 | 11.00 | 1.64±0.22 | 17.27±2.87 |
| 4 | 28 | 6 | 2.55±1.01 | 2.49±0.32 | 20.36±2.2 |
| 5 | 1422 | 13 | 20.61±3.55 | 3.49±0.05 | 26.24±0.32 |
| 6 | 10484 | 14 | 54.89±4.51 | 3.35±0.02 | 24.27±0.12 |
| 7 | 20873 | 14 | 76.46±5.14 | 3.33±0.02 | 23.47±0.08 |
| 8 | 18805 | 14 | 65.07±4.18 | 3.02±0.02 | 23.24±0.1 |
| 9 | 17841 | 14 | 62.6±4.27 | 2.94±0.01 | 22.99±0.1 |
| 10 | 19532 | 14 | 69.51±4.24 | 2.86±0.01 | 22.74±0.08 |
| 11 | 21453 | 14 | 76.62±4.84 | 2.81±0.01 | 22.56±0.08 |
| 12 | 22370 | 14 | 79.61±5.26 | 2.81±0.01 | 22.77±0.07 |
| 13 | 23799 | 14 | 80.4±5.37 | 2.85±0.01 | 22.85±0.08 |
| 14 | 25576 | 14 | 81.71±5.01 | 3±0.01 | 23.27±0.08 |
| 15 | 26351 | 14 | 82.61±5.16 | 3.05±0.01 | 22.92±0.08 |
| 16 | 22467 | 14 | 67.88±3.89 | 3.31±0.02 | 24.43±0.1 |
| 17 | 15588 | 14 | 53.57±3.19 | 3.47±0.02 | 25.07±0.1 |
| 18 | 7553 | 14 | 34.97±2.85 | 3.46±0.02 | 25.64±0.15 |
| 19 | 2215 | 13 | 27.35±3.38 | 3.26±0.04 | 25.15±0.29 |
| 20 | 42 | 5 | 7±3.4 | 2.16±0.13 | 24.74±2.06 |
| 21 | 22 | 2 | 5.5±2.33 | 1.8±0.13 | 29.41±4.38 |
| 22 | 2 | 1 | 2.00 | 2.41±0.48 | 24±2 |
| 23 | 18 | 2 | 9±8 | 1.88±0.16 | 20.33±2.45 |

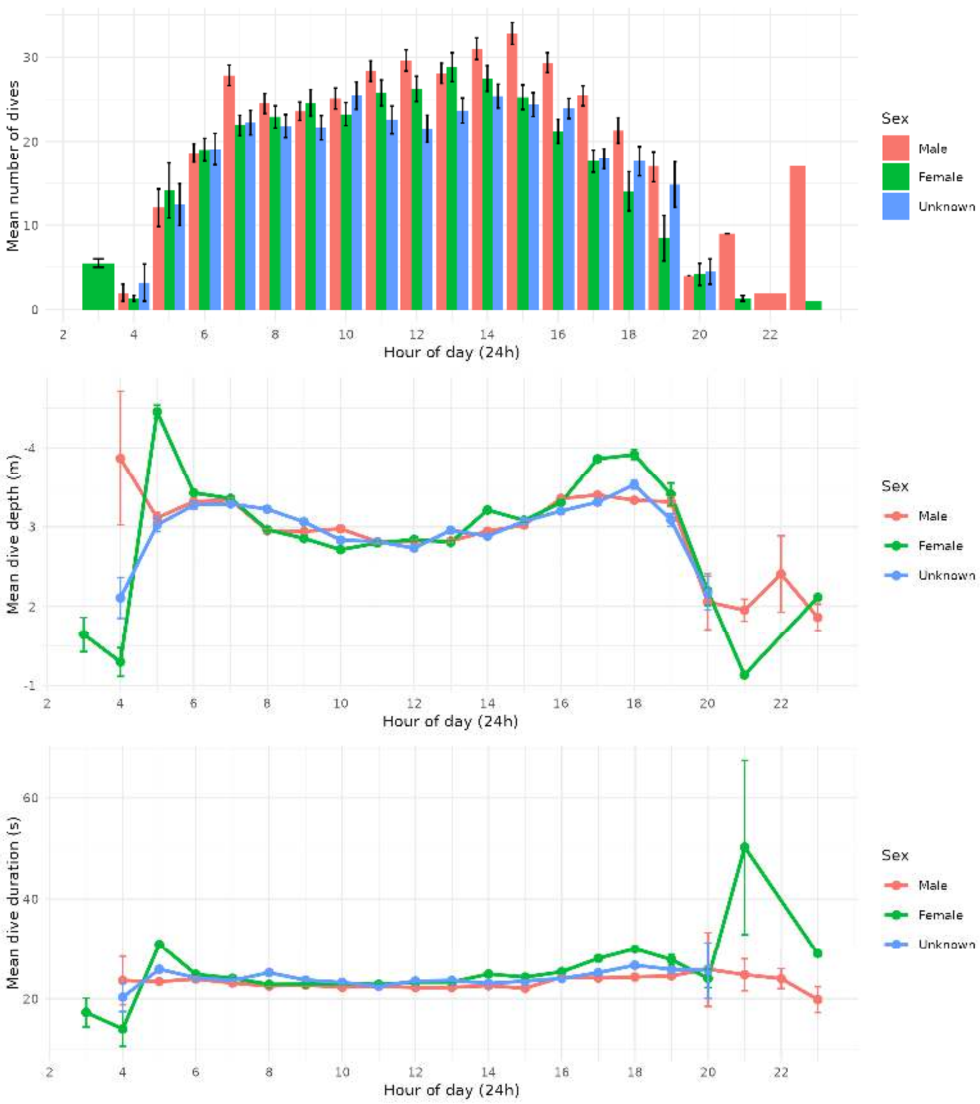



**Figure 5.** Daily patterns of male and female kawau tikitiki diving activity by male (red), female, (green) and unknown (blue) individuals. From top to the bottom: Mean number of dives and standard errors of each hour during the day; mean dive depth throughout the day; Mean dive duration throughout the day by hours.

### 3.2.2 Temporal overlap of dive and fishing data

We first assessed the temporal overlap between fishing events and diving activities, which helped us to identify and remove any fisheries records in hours that had no diving activities recorded for sequential spatial overlap analysis. As shown in Figure 6, set-net fishing occurs throughout the day and night, with a peak of activity in the morning (9 a.m.). There was no dive activity observed in kawau tikitiki between 11pm to 3am, hence we removed any fishing events records for sequential analysis (a further 25 records from 1912 records). The final fisheries data for overlap analysis consisted of 1887 recorded fishing events. The total fishing efforts by month are listed in table S1.

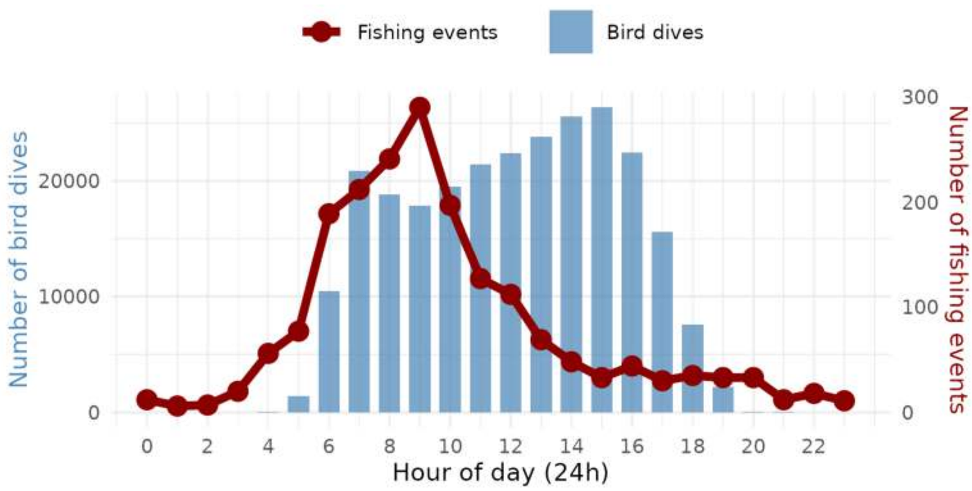



**Figure 6.** Temporal overlap between diving and fishing activities by hours.

### 3.2.3 Overlap of space-use of kawau tikitiki and set-net fisheries

We applied kernel density estimation (KDE) to delineate the core foraging areas of kawau tikitiki using all diving data and assessed their overlap with fishing activities (Figure 7). The number and percentage of fishing events inside each contour area/utility density surface are summarised in Table 2.

**Table 2.** Summary of fishing events that spatially overlapped with foraging areas of kawau tikitiki as identified by kernel density estimation.

| kernel density estimation | no. of fishing events | percentage (%) |
|---|---|---|
| 95% | 1041 | 55.16 |
| 50% | 104 | 5.51 |

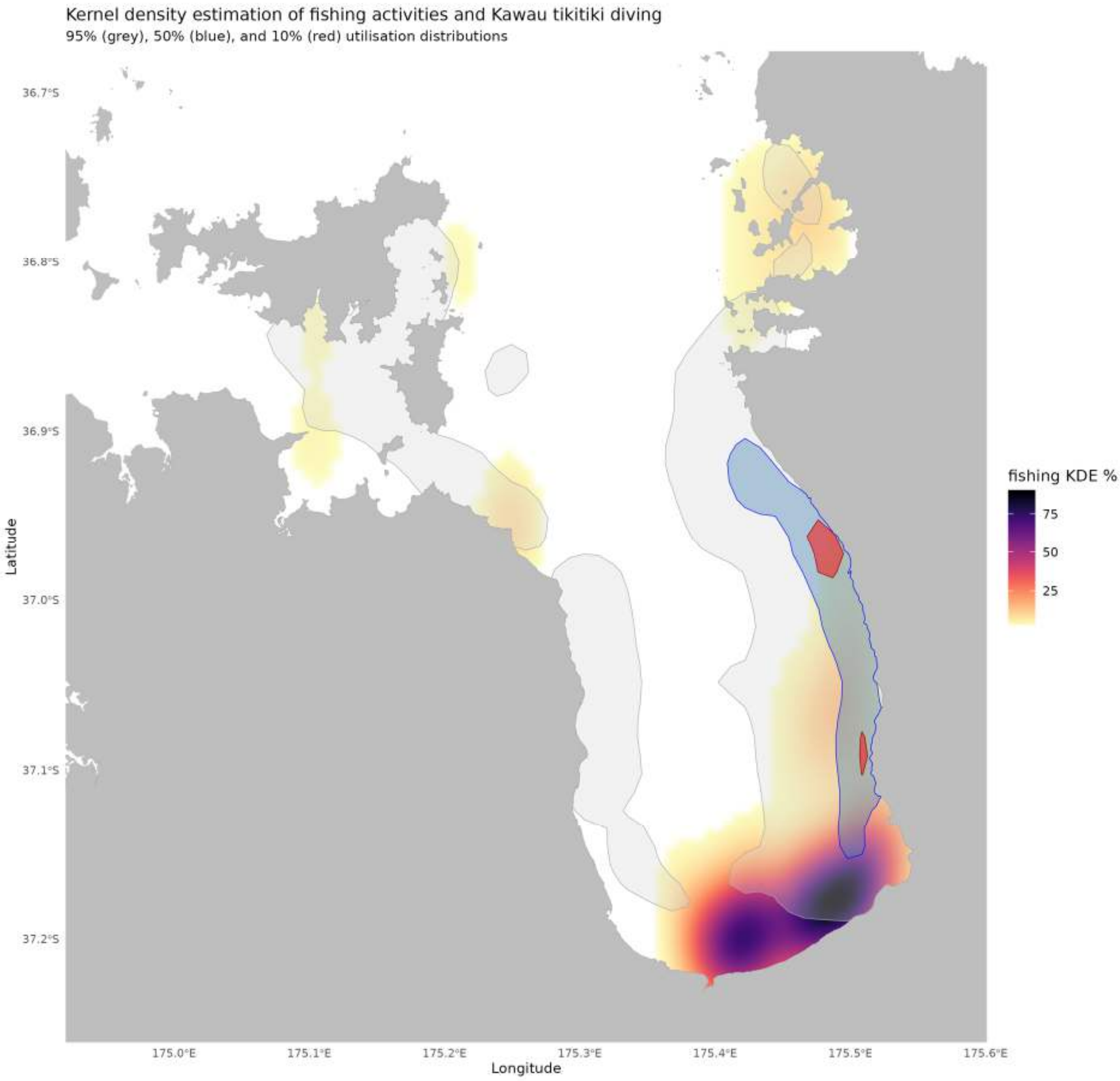
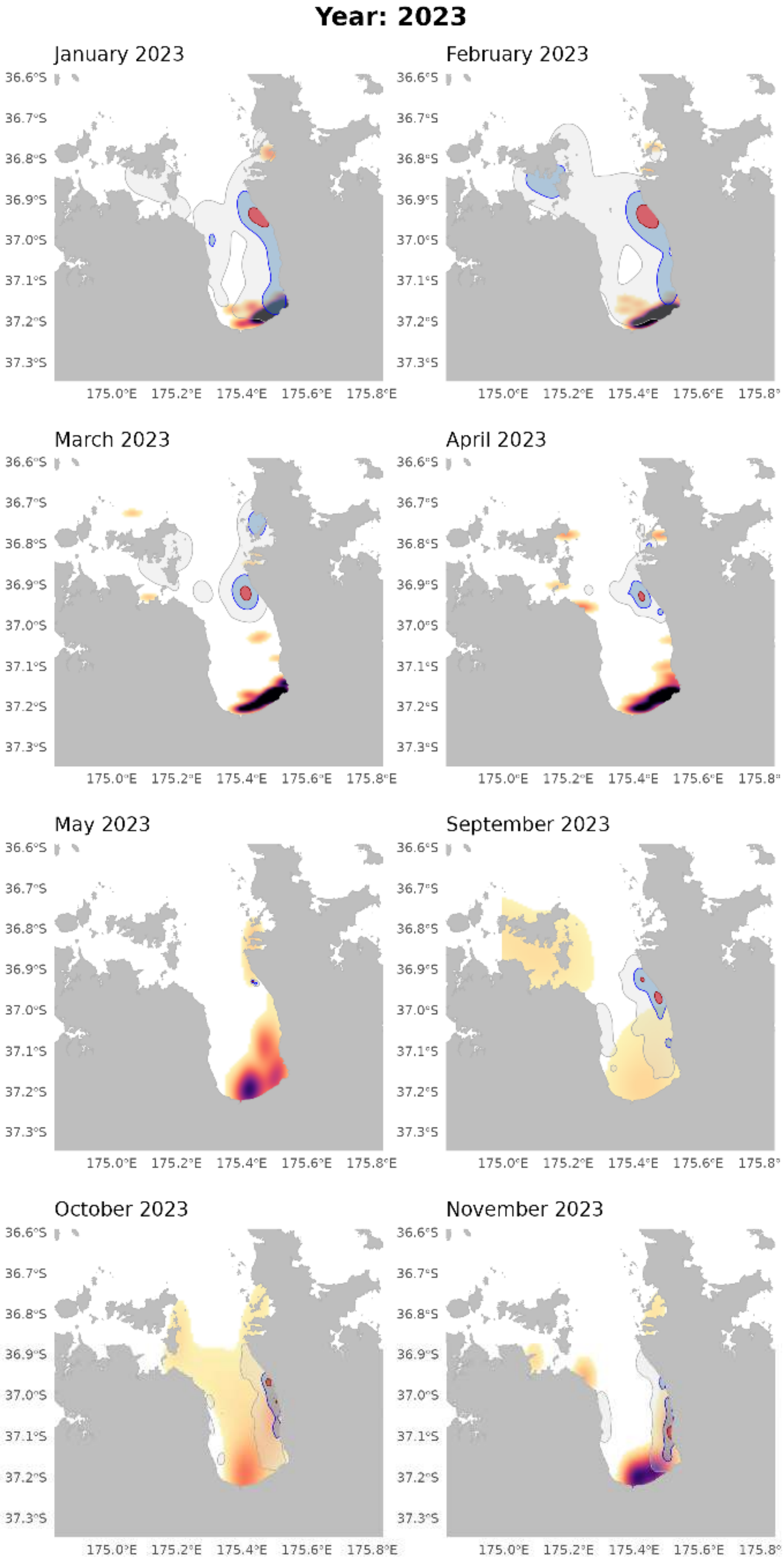



**Figure 7.** Spatial overlap between kawau tikitiki diving areas and fishing activities. The utilisation distributions represent different intensity levels of bird use: 95% contour (grey) represents the overall home range of the birds; 50% contour (blue) represents the core foraging areas; and 10% contour (red) represents the highest-use areas/activity hotspots. Kernal density surface of the fishing events > 3 were also generated with colouration to indicate the estimated density in percentage.

### 3.2.4 Monthly spatial overlap between kawau tikitiki and set-net fisheries

On average, 28.91% of fishing events happened in bird home range (95% utility distribution), and 6.48% of fishing events were in the core foraging area (50% utility distribution) across the months of the kawau tikitiki tracking. However, the spatial overlap between the space use of the bird and fishing activities shown a strong seasonal pattern (Figure 8). Kawau tikitiki used the east side and the inner Firth of Thames more, with larger core foraging areas during the spring – summer months, i.e., September – February. This was particularly acute from October to December when birds mostly foraged close to the shoreline Noth of Thames around Whakatete Bay and around another critical roost site at Tapu. During late summer and cooler spring months (March- May) foraging activity was mainly in the North of the Firth and in and around the deep water channels, during which time there was little overlap with commercial fishery operations (Fig. 9).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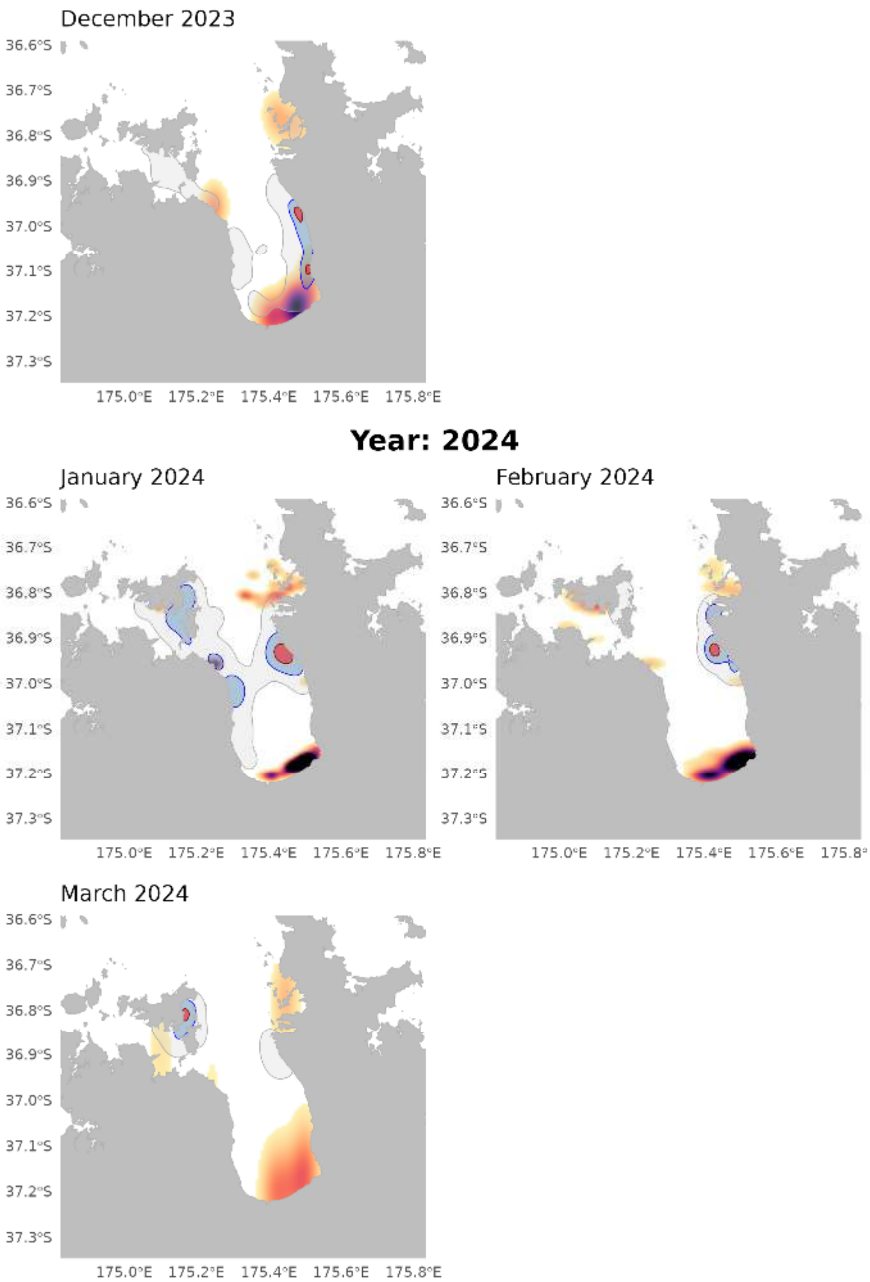


**Figure 8**. Monthly spatial overlap between bird diving areas and fishing activities. Each panel represents a different month, with bird utilisation distributions (95%, 50%, and 10% contours) and fishing activities (red lines). Kernal density percentage of the fishing events > 3 were used as a surface per month with lighter colour indicates low percentage and darker colour indicates high percentage.

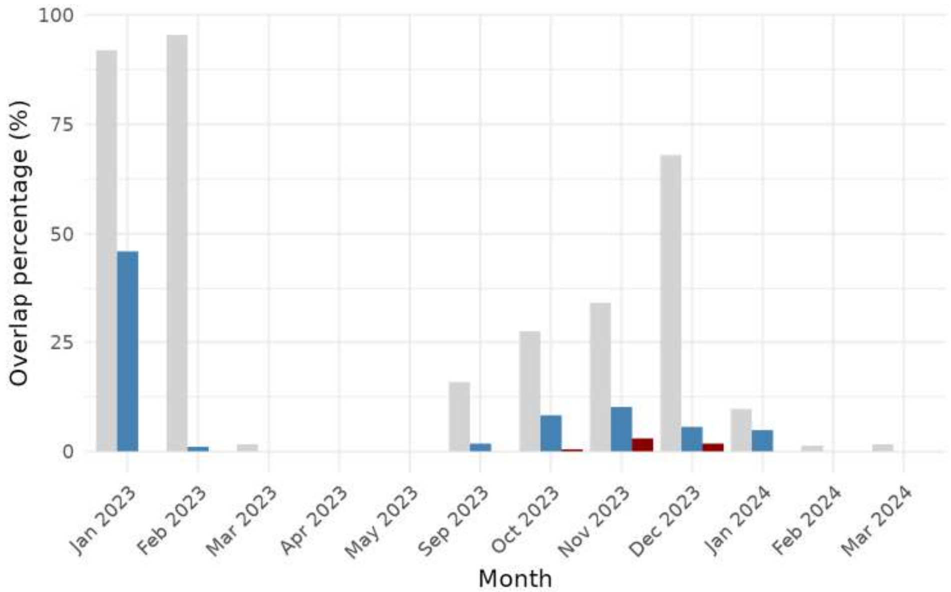


**Figure 9.** Percentage of monthly spatial overlap between bird diving areas and fishing activities across different utilisation distribution levels. The bars represent the percentage of fishing events occurring within each utilisation distribution area compared to total fishing events occurring in the same month.

### 3.2.5 Spatiotemporal interactions between kawau tikitiki and set-net fisheries

Although no species-specific proximity standard exists for spotted shags, we flagged any bird dive occurring within 300 m of a set-net fishing vessel during the same two-hour window from the fishing event as a potential interaction. We chose the 300 m buffer as a conservative operational boundary, consistent with marine transect methodologies commonly used to monitor seabird behaviour around vessels and nets (Cianchetti-Benedetti, 2018; Richard et al. 2011). We identified 28 occasions of interaction of five birds (two males, two females and one unknown) diving within the distance threshold at approximately the same time window of four fishing records. The distances from the dives to lines between the fishing starting and ending locations ranged from 49.76 – 296.04 m (Table 3). All 28 dive interactions occurred within the time window of 5 November to 5 December 2023, and were located on the east coast of the Firth of Thames (Figure 9). Among the 28 dive records, 20 dives from three tracked birds were in the morning between 7:26 a.m. to 8:49 a.m. Noticeably, all three birds were interacting with one specific fishing event (Figure 10 and 11). A further four records from the same bird were in the middle of the day, and four records from another individual were in the late afternoon.

**Table 3.** Summary of interaction events based on the distance between fishing vessels and kawau tikitiki dive records.

| distance between dive and fishing event | count of interactions in the | percentage |
|---|---|---|
| 0-50 | 1 | 3.57 |
| 50-100 | 1 | 7.14 |
| 100-150 | 2 | 14.29 |
| 150-200 | 4 | 28.57 |
| 200-250 | 11 | 67.85 |
| 250-300 | 8 | 100.00 |

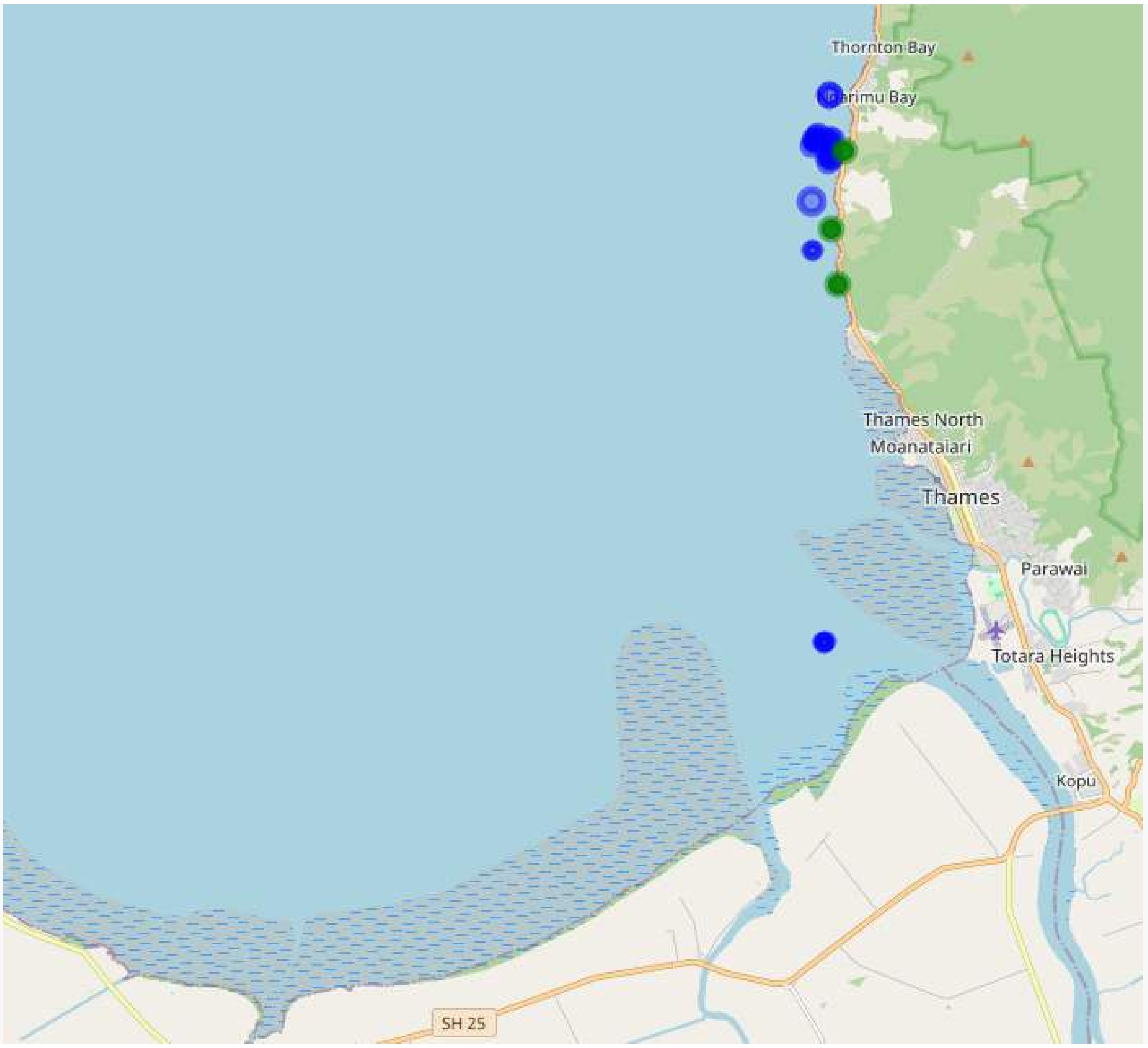


**Figure 10.** Map of the Firth of Thames and locations of potential interactive events between fishing and diving of kawau tikitiki. The blue circles show the locations of the dive where fishing-bird interaction events were identified, the green circles indicate the day roosts of the kawau tikitiki.

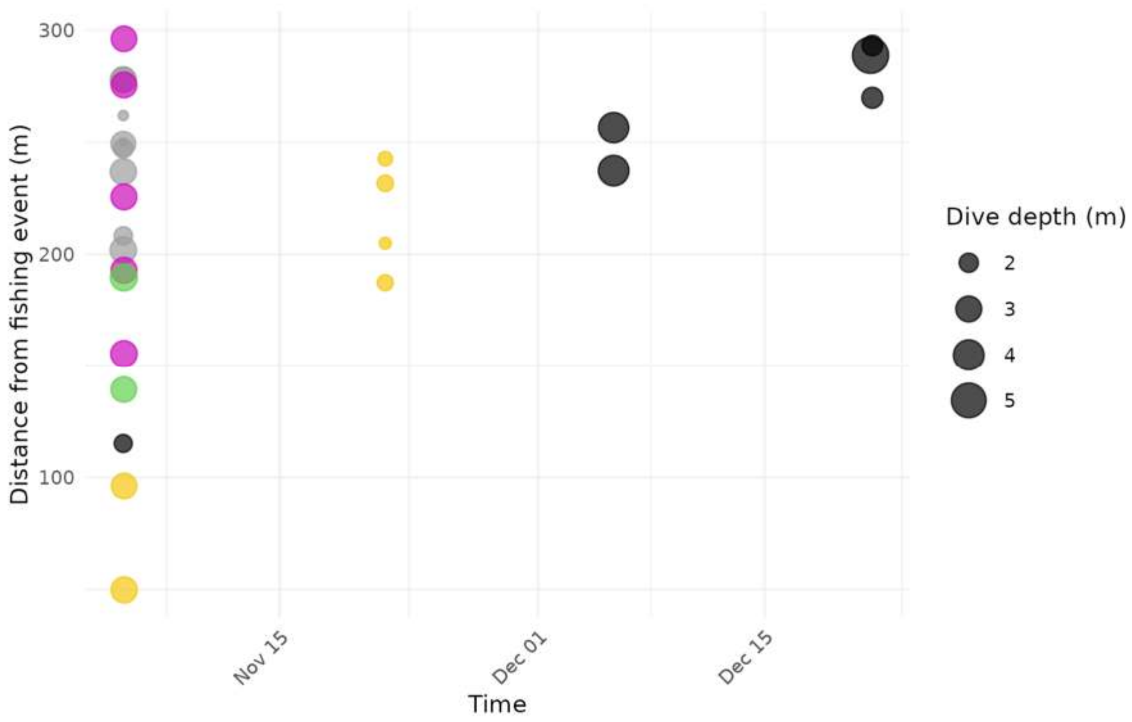


**Figure 11.** Temporal analysis of interactions between fishing and diving of kawau tikitiki. Different tracked individuals are indicated by different circle colours. Dive depth is indicated by the size of the circle.

# 4 Discussion

This study provides the first fine-scale analysis of the spatiotemporal overlap between the foraging behaviour of kawau tikitiki and commercial set net fisheries in the Firth of Thames. Our results reveal a convergence of bird foraging activities and fishing efforts in both space and time, highlighting a clear seasonal window of elevated bycatch risk. Four key patterns emerge from the analysis: (1) seasonal shifts in foraging distribution, including use of mussel farms and a pronounced spring concentration on the Thames coastline; (2) strong spatial overlap between core foraging areas and set net operations during the spring; (3) a temporal overlap, with net-setting activity peaking during the birds’ morning foraging activity; and (4) sex-based differences in dive behaviour that may influence individual vulnerability to entanglement.

## 4.1 Seasonal Movement and Habitat Use

Kawau tikitiki exhibited clear seasonal shifts in their foraging habitat. In September and from March to June, individuals made more use of mussel farms in the Northern Firth of Thames and off Waiheke, where they performed deeper and longer dives. This pattern is likely related to high fish prey availability associated with aquaculture infrastructure (Underwood and Jeffs 2023). In contrast, during spring and early summer (September – December), the birds concentrated their foraging around the southern Firth, particularly the western Coromandel coast and the Waihou River mouth. This spatial shift suggests a seasonal aggregation in response to naturally available prey, such as spawning fish or estuarine baitfish runs (Smith 2014).

While not the primary focus of this report, it is worth noting that broader environmental drivers may also influence the seasonal movements of kawau tikitiki. Late summer warming in the southern Firth, in association with high nutrient loads from major river mouths, creates a hypoxic marine environment that likely alters prey availability or suitability, prompting a seasonal northward movement of the birds (Green and Zeldis 2015).

## 4.2 Overlap with set-net fisheries

### 4.2.1 Spatial overlap in the southern Firth

The spring (October - December) congregation of kawau tikitiki in the southeast Firth also coincides spatially with a concentration of set net fishing activity. Kernel density analysis revealed that on average nearly 30% of fishing events fell within the birds' home range over the tracking period. Notably, these overlaps were most prominent during November and December, when birds were foraging intensively near shore and in close proximity to known roost sites along the Thames coastline (Figure 1). Given similar amounts of diving records from nine individuals were recorded from September to February, we identified all the direct interaction events during concurrent time windows — 28 dives by five individuals occurred within 300 m of active fishing events. These interactions, although relatively rare, are significant given the small population size and the likelihood that such events represent a minimum estimate of true overlap.

The significance of this level of overlap becomes clear when scaled to the population level. Over the 1352 bird-days of observation (14 birds tracked for an average of 96.6 days), 28 interactions with set-nets were recorded. Assuming these events are representative, and scaling to the estimated regional population of ~600 breeding birds, this suggests a possible 1200 potential interactions over a comparable 96.6-day spring period. While the exact fatality rate per interaction is unknown, even a small proportion of these interactions result in death, such as 0.1% to 0.5%, this would equate to 1 to 6 bird fatalities through bycatch — a potentially significant toll for a declining population of this size. It is also notable that approximately 37% of fishing data had to be excluded during screening due to errors or implausible values, suggesting that these estimates may be conservative.

Finally, this analysis only deals with commercial fisheries in a region with a significant recreational set net fishery (Green et al. 2020), for which we currently have no data on distribution and impact. Anecdotal observations of dead beach cast shags (kawau tikitiki and pied shags) in otherwise good condition and plumage suggest the total impact of nets in the region may be significant.

### 4.2.2 Temporal Overlap: Morning Risk Window

Analysis of dive behaviour confirmed kawau tikitiki are strictly diurnal foragers, with foraging effort peaking between 6 a.m. and 10 a.m. Set-net fishing activity was also high during this time, particularly between 8 a.m. and 10 a.m., creating a clear temporal window of elevated risk. Of the 28 direct dive-fishery interactions identified, nearly 70% occurred during this morning window. This alignment between peak foraging and net-setting increases the likelihood of bycatch, especially for individuals diving near the seabed or in turbid, estuarine waters where visibility is limited.

## 4.3 Sex-based diving differences

While the sample size was limited, the summary statistical metrics showed males consistently performed more dives, and dived deeper but for shorter durations, than females across the day on average. This may increase their exposure to set nets. These patterns suggest that male kawau tikitiki are vulnerable to set nets, as they have a higher likelihood of encountering them either during dives or while searching and foraging underwater, particularly in areas of high fishing intensity.

Although sex was not a strong predictor in all mixed-effect models, the observed differences suggest that vulnerability may vary demographically within the population — an important consideration for population viability given the small breeding size of the northern North Island population.

## 4.4 Conservation implications and recommendations

Our results highlight a seasonal and spatially explicit risk to kawau tikitiki from set net fisheries in the Firth of Thames, particularly in spring when most of the population concentrates near the Thames coast. We make the following recommendations to reduce the potential threat to kawau tikitiki from set net fisheries:

- **Seasonal spatial closures:** Temporal restriction of set netting in the southern Firth (especially the western Coromandel coast and Thames coastline) from November to January.
- **Time-of-day restrictions:** the peak of fishing occurred during the morning hours, where most of the direct interactions from this study were identified. The kawau tikitiki foraged actively from 7 a.m. to 5 p.m., peaking at 2–3 p.m. While the spatial overlap might be the main reason for the bird-fisheries interactions, time-of-day restrictions can also be implemented as a management method.
- **Fisheries monitoring:** Identity high-risk areas, for example southeast of the Firth of Thames, and introduce mandatory observer coverage or electronic monitoring on vessels operating during the spring aggregation period.
- **Fisher engagement:** Collaborate with local fishers and MPI to trial gear modifications or mitigation strategies and to raise awareness of the issue.
- **Ascertain recreational impact**: There is a need for better understanding of recreational set net activities and its overlap with kawau tikitiki foraging habitat. Conduct coastal surveys along the Thames coast to ascertain the level of recreational set netting occurring in critical foraging habitats. Additionally, obtain detailed location and size data of seabird colonies by species to improve spatial overlap assessments.
- **Roost site protection**: Consider working with local DOC offices or regional councils to more actively protect known key roost sites from land-based disturbance.

Given the documented mortality of tagged birds and the identification of repeated spatiotemporal overlap, these measures are warranted and urgent.

## 4.5 Limitations and future research

This analysis was based on a modest sample of 14 birds over a single annual cycle. Sex ratios were uneven, and shallow dives (<0.5 m) may not have been recorded due to the wet/dry sensor noise. Full flight trajectories were not captured, which limited assessment of foraging trip duration and direction. Kawau tikitiki are known to be communal hunters, and multiple individuals may interact with the same fishing event (Lalas 1983).

Nevertheless, consistent seasonal and temporal patterns across individuals point to robust population-level patterns. Given the substantial and representative diving dataset already available, we do not expect further data collection to substantially alter these patterns. However, if additional data are collected, efforts should focus on improving demographic representation in tagging—particularly balancing sex ratios and including both juvenile and adult spotted shags.

 

Future research work could aim to:

- **Link dive data with observer data** from set net vessels to identify potential direct interactions between fishing activities and the foraging behaviour of spotted shags. Also, future research should seek to better understand fishing methods that target different fish species, as well as the fishing temporal patterns such as associated with tide and weather in estimate the risks of interactions.
- **Explore mitigation strategies**, including gear modifications and exclusion zones with temporal dynamics over seasons.
- **Quantify the size of the recreational set-net fishery** with core kawau tikitiki habitats, using integrated approaches (e.g., coastal surveys, cell phone or tracking data).

## 4.6 Final remarks

This study provides critical new insights into the behavioural ecology of kawau tikitiki and their exposure to set net fisheries. The clear spatiotemporal overlap between foraging behaviour and fishing activity presents an urgent conservation concern for this declining and genetically distinct seabird population. Targeted, evidence-based management measures, particularly seasonal closures and improved monitoring, offer an immediate pathway to reducing bycatch and ensuring the persistence of this iconic species in the Hauraki Gulf.

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# Supplementary materials:

Tabel S1: Summary of fishing events by month during the study period.

| Year | Month | No. of fishing events |
|---|---|---|
| 2023 | January | 59 |
| | February | 77 |
| | March | 108 |
| | April | 74 |
| | May | 66 |
| | June | 108 |
| | July | 102 |
| | August | 148 |
| | September | 139 |
| | October | 159 |
| | November | 146 |
| | December | 96 |
| 2024 | January | 133 |
| | February | 142 |
| | March | 106 |

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