



Testing the effectiveness of integrated pest control at protecting whio (*Hymenolaimus malacorhynchos*) from stoat (*Mustela erminea*) predation in beech forest (Nothofagaceae)

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Abstract: The introduction of mammalian predators, particularly stoats (*Mustela erminea*), to New Zealand led to the decline in whio (*Hymenolaimus malacorhynchos*), an endemic riverine duck. Stoat control for whio in the South Island has focused on valley floor trapping along waterway margins but increasing survival and productivity for whio using this method is complicated by irruptive predator dynamics caused by occasional masting of beech species (*Nothofagaceae*). We investigated the effect of integrating stoat trapping with pulsed aerial 1080 toxin operations to counter predator irruptions on whio survival and productivity in c. 40 000 ha of beech dominated Kahurangi National Park. We collected data on adult female whio survival, probability of breeding, nesting success, and duckling survival for seven years through two full beech mast events. We found a positive relationship between distance into the interior of the treatment block and whio population growth, nesting success, duckling, and adult survival. Heavy female whio were more likely to breed than light ones, and adult female survival was higher during the breeding season than during non-breeding. Nesting success was greatest in the breeding season following a 1080 operation. Duckling survival was higher at lower river flows. Positive population growth was only predicted near the centre of the study area (c. 13 km from the edge) with both traps and 1080. We conclude that in the centre of treatment blocks at least as large as our study block, integrated pest control should be enough to ensure long-term population persistence of whio in a beech-dominated system.

Keywords: 1080, blue duck, Kahurangi National Park, New Zealand, radio tracking, riverine duck, traps

Introduction

New Zealand's biota has high levels of endemism and evolved in the absence of mammalian predators (Brown et al. 2015). The introduction of mammalian predators to New Zealand resulted in significant declines and extinctions of many native bird species largely because the biota had few defence mechanisms (Clout 2001; Duncan & Blackburn 2004). One of the species that has declined is whio (blue duck *Hymenolaimus malacorhynchos*), an endemic specialist riverine duck classified as Endangered by the IUCN (www.iucnredlist.org/version/2018-1) and Nationally Vulnerable by the Department of Conservation (DOC) (Robertson et al. 2017).

In the last two decades it has become apparent that the major agent of decline for whio is predation by introduced mammals, particularly stoats (*Mustela erminea*; Whitehead et al. 2007; 2008; Glaser et al. 2010). Whio are ground nesters with low productivity compared to other ducks (Williams 1991). Only females incubate, making them more vulnerable to predation while on the nest, which leads to a male-biased sex ratio where introduced mammalian predators are not controlled (Glaser et al. 2010). Whio have declined in distribution (Fordey

1976; Williams 1988; Cunningham 1991; Studholme 1999), and abundance (Glaser et al. 2010), and now mostly occur in fragmented populations in the headwaters of rivers (Glaser et al. 2010). Glaser et al. (2010) estimated there were at most 2500–3000 whio nationally, and there is low overall genetic diversity (Grosser et al. 2017). The two island populations are genetically distinct (Grosser et al. 2017). In the South Island, whio often inhabit waterways surrounded by southern beech (*Nothofagaceae*) forest, which Wardle (1984) noted seed in a mast event every two to six years but may now do so more frequently because of global warming (Richardson et al. 2005). Increased food availability from mast seeding of beech trees results in an increase in rodent populations, and subsequently stoat populations (King 1983), which, in turn, leads to higher rates of predation of birds (Murphy & Dowding 1995, White & King 2006) probably including whio.

In 2009, eight sites were established nationally for the protection of whio, including the Wangapeka/Fyfe catchments in Kahurangi National Park, with the aim of creating self-sustaining populations of at least 50 whio pairs at each site (security sites, Glaser et al. 2010). At these sites landscape-scale predator control through trapping is often impracticable because

of steep and/or incised mountainous terrain, particularly in the South Island. As a result, trapping programmes in the South Island have primarily focused on linear protection of waterways with trap-lines along valley floors (low-intensity stoat trapping). Whitehead et al. (2010) found that low-intensity stoat control improved performance of whio populations in Fiordland but was insufficient to ensure long-term population persistence.

Sodium fluoroacetate (1080) has been used as a toxin for more than 50 years in New Zealand to control possums (*Trichosurus vulpecula*) for the protection of forests or to prevent the spread of bovine tuberculosis. This poison has been used more recently to control rats (*Rattus* spp.), and stoats, for the benefit of bird populations, particularly when their numbers rise in response to beech mast events (Elliott & Kemp 2016). Integrated pest control, with continuous stoat trapping and pulsed aerial application of 1080, is effective at mitigating the impacts of predation by introduced mammals on birds in a beech forest dominated system (O'Donnell & Hoare 2012).

This study investigates the effectiveness of integrated pest control using continuous low-intensity stoat trapping, combined with three aerial 1080 operations, including two in response to beech mast events, on adult female whio survival and productivity over a seven-year period in the Wangapeka/Fyfe catchments. The objectives were to determine: (1) whether integrated pest control effectively protects adult female whio, their nests and ducklings from stoat predation in the breeding season(s) following an aerial 1080 operation; (2) how whio survival and productivity is affected by distance to the edge of the treatment block, and by river flow; and, (3) whether integrated pest control is likely to result in long-term persistence of a South Island whio population in a beech forest dominated system.

Methods

Study area

Pest control and whio survival data were collected between August 2011 and May 2018 in the Wangapeka/Fyfe catchments (c. 40 000 ha; 172.5°E 41.5°S) in Kahurangi National Park, New Zealand (Fig. 1). This site is dominated by silver beech (*Lophozonia menzeisii*) forest above 1100 m a.s.l., red beech (*Fuscospora fusca*) at about 700–1100 m a.s.l. and hard beech (*F. truncata*) at < 700 m a.s.l. The area is steep and mountainous with the treeline at about 1300 m a.s.l. The study site waterways are steep, mobile, fast-flowing rivers with numerous side-streams, pools, and steep-sided gorges. Whio surveys in the late 1990s found one pair along the Rolling River and another six pairs in the greater Wangapeka catchment, plus numerous single birds (Studholme 1999). Whio management started at this site in 2003 when the first 3.6 km of trap-line was deployed and the first captive-raised whio juveniles were released to supplement the population. As of May 2017, the Wangapeka/Fyfe Whio Security Site held at least 43 pairs, just short of its national objective of 50 pairs (Glaser et al. 2010).

Predator control operations

Initially, the linear river-edge low-intensity stoat trapping programme consisted of single or double trap-lines comprising single-set DOC150 or DOC200 traps inside wooden tunnels spaced at 100 m intervals. The complete trapping network for the Wangapeka/Fyfe covers 85.8 km of waterway (Fig. 1). In June 2015, the single-set trap design was replaced with double-set trap boxes (Glaser & Smart 2004). Trap checks occurred monthly in non-1080 years (excluding June and July) and re-baited with either Erayz#8 (dried rabbit-based bait

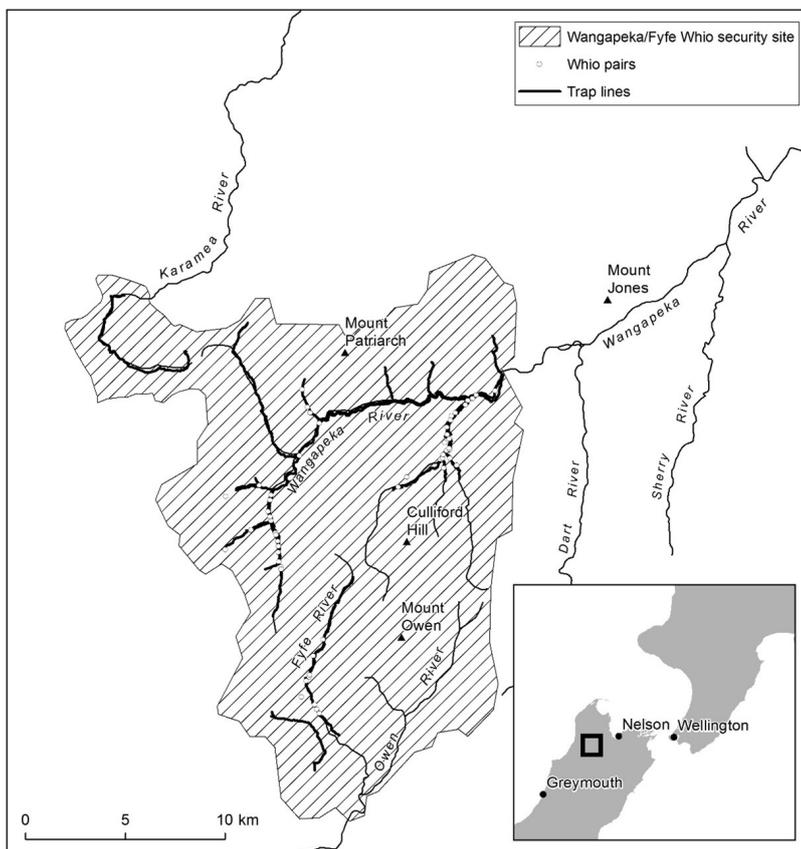


Figure 1. Location of the Wangapeka/Fyfe whio security site (c. 40 000 ha) including trap-lines and locations of monitored pairs.

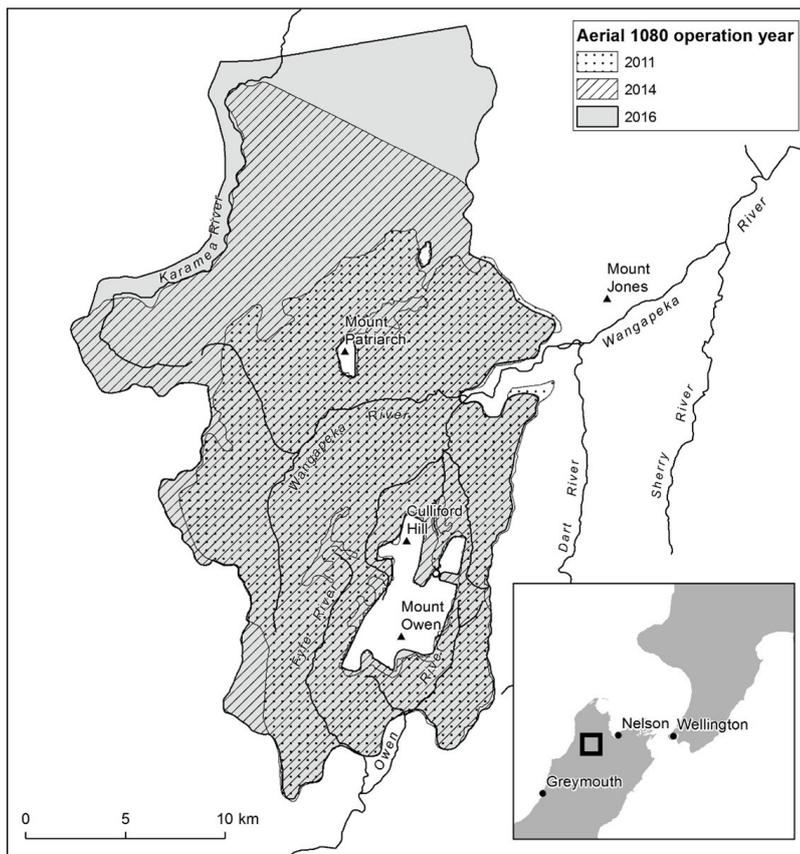


Figure 2. Location of the Wangapeka/Fyfe aerial 1080 treatment blocks in 2011, 2014, and 2016.

from Connovation Ltd) or fresh eggs. Following the spring 1080 operations, trap checks occurred in December, January, March, and May until the following August when the monthly trap maintenance programme resumed.

Aerial 1080 operations using cereal baits containing 0.15% 1080 were sown by helicopter across the site in 2011, 2014 and 2016 (with alpine exclusions) (Fig. 2). Up to six weeks before each toxic application, 6 g non-toxic baits were sown. The first 1080 operation was in September 2011 (29 000 ha), carried out by TBFree NZ (then Animal Health Board) to control possums using 12 g RS5 pellets at an application rate of 2 kg ha⁻¹. This was followed by 1080 operations in October 2014 (44 000 ha) and October 2016 (51 000 ha) carried out by DOC in response to full beech mast events (> 4000 seeds m⁻², Wardle 1984) (Elliott & Kemp 2016). The second and third operations were targeting rats with a secondary poisoning of stoats, so used an application rate of 1–2 kg ha⁻¹ (6–12 g RS5 pellets) in 2014 and 1.5 kg ha⁻¹ (6 g RS5 pellets) in 2016 (Fairweather et al. 2018). The effectiveness of the aerial control operations was assessed by monitoring the relative abundance of rats using footprint tracking tunnels (King & Edgar 1977) following the protocol of Gillies & Williams (2013). Rodent abundance is an important driver of stoat abundance and rodents are vectors of poison to stoats (Kemp et al. 2018).

Whio monitoring

Whio were monitored in the Rolling River and tributaries, South Branch Wangapeka River and tributaries, and Fyfe River (Fig. 1). Nest monitoring was carried out in six (2011, 2012, 2013, 2015, 2016, and 2017) of the seven breeding seasons (September–December). In 2014, monitoring was not detailed enough to determine the cause of nest or whio mortality, so

these data were excluded from all analyses.

Adult whio were captured by driving them into nets secured in/across the river (Glaser & Smart 2004) and all captured birds were weighed, colour banded and fitted with passive RFID transponders for unique identification. Adult females in the nest study were fitted with 16 g radio-transmitters, which were 2% of the average body weight of a female whio (two-stage VHF SirTrack or Advanced Telemetry Systems, with a mortality switch), using an external flying bird backpack harness (Glaser & Smart 2004). Transmitters were changed, or at least checked, annually with an expected life ranging from 18 months (SirTrack with a 14-hour duty cycle) to 36 months (ATS with an 8-hour duty cycle).

Each year, 10–14 radio-tagged females were intensively monitored during the breeding season and their survival was checked during the subsequent moulting period (February–May) and again after the winter. Throughout the study, adult female whio caught for transmitter fitting, removal or checking (usually during late autumn or winter) were weighed and their plumage around the transmitter inspected. All recently dead whio found were collected for autopsy.

Nest monitoring

At the beginning of each breeding season, radio-tagged adult females were tracked once every 10–14 days to establish whether they were gravid or nesting. Nests were found on foot using radio telemetry, and at least one infrared trail camera was set up within 2 m of accessible nest entrances to monitor nest fate and cause of nest failure. Cameras and/or nests were checked regularly. Nests were considered successful if at least one egg hatched.

Duckling survival

Duckling survivorship was monitored in two ways:

(1) intensive monitoring of the broods of the subset of radio-tagged whio between hatching and fledging; and,
 (2) by conducting two full counts of all the ducklings in each identifiable pair's territory in our study areas; one soon after most nests had hatched and another at about the time that ducklings fledged. This method included all broods used in the first method.

For intensive monitoring, once ducklings were on the water, radio-tagged females were checked once every 10–14 days until the ducklings were 4 weeks old and then, where possible, every 14–21 days until the ducklings had fledged. Data were collected from intensively monitored broods until ducklings were 60 days old. Up until they were 60 days old, the disappearance of a duckling was regarded as indicating its death because they do not leave their natal range before then. When ducklings died, their bodies were never found, so we could not determine cause of death.

Data analysis

We investigated the relationships between adult female survival, probability of breeding, nesting success, duckling survival and a range of covariates that we predict influence productivity and survival. Covariates included:

- (1) Site: One of 10 catchments within our study area.
- (2) Year: One category for each year of our study, with each year running from 1 September to 31 August.
- (3) Season: Categorized as either (a) breeding season (September–December) or (b) non-breeding season (January–August).
- (4) River flow ($\text{m}^3 \text{s}^{-1}$) on the previous day (flow) collected by the Tasman District Council (TDC) c. 5 km down the Wangapeka River from our study area.
- (5) Average river flow ($\text{m}^3 \text{s}^{-1}$) on the previous 10 days (flow10) (TDC recorder).
- (6) Whether the river was in flood on the previous day (flood), (TDC recorder).
- (7) Number of days during which the river was in flood in the previous 10 days (flood10) (TDC recorder).
- (8) Number of floods during the non-breeding season (winter flood), defined as any river flow exceeding three times the median flow (Clausen & Biggs 1997).
- (9) Distance from a nest to the nearest trap (m).
- (10) Distance to untreated land (m): distance from a nest or the place where a whio was first caught or seen to the nearest untreated native forest. For the purposes of this analysis, we defined untreated forest as being a catchment with no traps, or land which had not been treated with 1080 for more than a year.
- (11) Distance to the nearest farmland (m).
- (12) Time since 1080 operation; three possible categorisations were used to examine the longevity of any effect of 1080:
 - (a) Time since 1080(1); 3 categories: < 6 months after a 1080 operation, 6–18 months after a 1080 operation and more than 18 months after a 1080 operation.
 - (b) Time since 1080(2); 2 categories: < 6 months and > 6 months after a 1080 operation.
 - (c) Time since 1080 (3); 2 categories: < 18 months and > 18 months after a 1080 operation.

All analyses were implemented in program R (version 3.6.3) (R Core Team 2020). We used AIC (Akaike Information Criteria: AICc for small sample sizes and QAIC for over dispersed models) for model selection (Burnham & Anderson

2002). Burnham and Anderson (2002) suggest that models within $2\text{AIC} < \text{units}$ of the best model have substantial support and thus can be confidently used for making inferences, while models with greater than 10 AIC units from the best model, essentially have no support.

Adult female survival

Adult female survival was estimated, and relationships between survival and possible explanatory variables explored, using the “Nest survival” method of Dinsmore et al. (2002) implemented in the package RMark (version 2.2.7) (Laake 2013). This method estimates mean daily survival (which is converted to annual survival by raising daily survival to the power of 365). It is well suited to analysing survival data collected from radio-tagged animals whose survival is monitored at irregular intervals (Rotella et al. 2004). We constructed plausible models using seven variables: season, time since 1080(1), time since 1080(2), time since 1080(3), distance to untreated land, distance to farmland, flood, flood10, flow, and flow10. Plausible models included only one of the river flow variables, only one of the time since 1080 variables, only one of the distance variables and no interaction terms. We could not usefully examine overdispersion in these models as there are no well-developed tools for its estimation for these kind of data (Rotella et al. 2004).

Female weight and transmitters

We used Generalised Linear Models (GLMs) with normal errors to examine the possible impact of transmitters on female weight.

Probability of breeding

We examined factors affecting the probability of breeding in two ways.

- (1) We modelled the relationship between the probability of breeding and winter weight of birds that we weighed using a GLM and assuming a Bernoulli distribution.
- (2) We modelled the relationship between three covariates: year, site, and winter floods and the probability of breeding of a larger number of whio using a binomial GLM. For this analysis whio were grouped into adult pairs of ducks by year and site, and a sample comprised all the pairs of whio in a year at a site, and the metric examined was the proportion of pairs that bred. This enabled explicit examination of overdispersion.

Nesting success

Nesting survival was estimated and the relationship between survival and possible explanatory variables explored using the same methods used to examine adult survival (Dinsmore et al. 2002). Daily nest survival was converted to nest success by raising daily survival to the power of the length of the incubation period (34 days). A suite of plausible models included covariates for time since 1080(1), time since 1080(2), time since 1080(3), distance to the edge, distance to trap, flood, flood10, flow, and flow10. Only one river flow and one time since 1080 variable was included in each plausible model and interaction effects were not examined.

Duckling survival

Survival of intensively monitored ducklings was estimated using the same methods as adult survival (Dinsmore et al. 2002). Estimated daily survival was converted to fledging

success by raising daily survival to the power of the length of the fledgling period (60 days). A suite of plausible models included covariates for time since 1080(1), time since 1080(2), time since 1080(3), distance to untreated forest, distance to farmland, flood, flood10, flow, and flow10. Only one river flow variable, one time since 1080 variable, and one distance variable was included in each plausible model. We also explored the possibility that duckling survival might vary with age by incorporating duckling age as a second order polynomial relationship between age in days and duckling survivorship in some models.

Duckling survival from the two counts was examined using binomial GLMs where the proportion of ducklings in each brood that survived till the second survey was regressed against combinations of one of the three time since 1080 variables and one of the distance variables. We accounted for overdispersion in these models by using the QAICc (Burnham & Anderson 2002).

Population modelling

To explore the consequences of our findings on the likely population trajectories of whio populations managed with integrated predator control we used staged-based Lefkovich matrices (Lefkovich 1965) to estimate adult female population growth rates (λ). Our matrices included three stages (duckling, juvenile and adult) and we explored four scenarios: (1) Whio populations near the centre of the block (c. 13 km from the edge) with trapping only, (2) whio populations near the centre of the block with trapping and 1080 applied aerially once every 3 years, (3) whio populations at the edge of the block with trapping only, (4) whio populations at the edge of the block with trapping and 1080 applied aerially once every 3 years.

Population parameters used in the matrices were derived from this study or were taken from Whitehead et al. (2010). Population growth rates were estimated from the dominant

eigenvalue of the matrices and uncertainty in growth rates was simulated by parametric bootstrapping (Williams et al. 2002) using the estimates of the demographic parameters and their standard errors.

Results

Predator control operations

Full beech mast events (all three species seeding) were recorded in 2014 and 2016 and a partial red beech mast in 2012. The rat tracking rate in the Wangapeka catchment dropped immediately after each aerial 1080 operation but the decline was short-lived in both the 2011 and 2014 operations (Fig. 3). The 2011 aerial 1080 operation was followed by a partial beech mast event in 2012, which led to an increase in rats and the operation in 2014 was not as effective as planned. Consequently, there was a rapid recovery in rat abundance (Fig. 3). However, the 1080 operation in 2016 reduced rat tracking to 0% and the tracking rate remained low for the following nine months.

Adult female survival

We monitored 55 radio-tagged adult female whio for 30–1334 days each. Nineteen monitored females died: five showed no sign of being preyed upon, 13 (68%) showed signs of having been preyed upon, and the body of one was not recovered. Seven of the birds that were apparently preyed upon were confirmed as stoat kills. Four females were killed by stoats during the moult period (February–May), two were killed by stoats during the breeding season and one was killed by a stoat in winter (June–July). No female was filmed or photographed being killed by a predator while on the nest and no female was found to have died because of ingesting 1080 pellets.

Of the plausible models of the relationship between adult female survival and possible explanatory variables that we

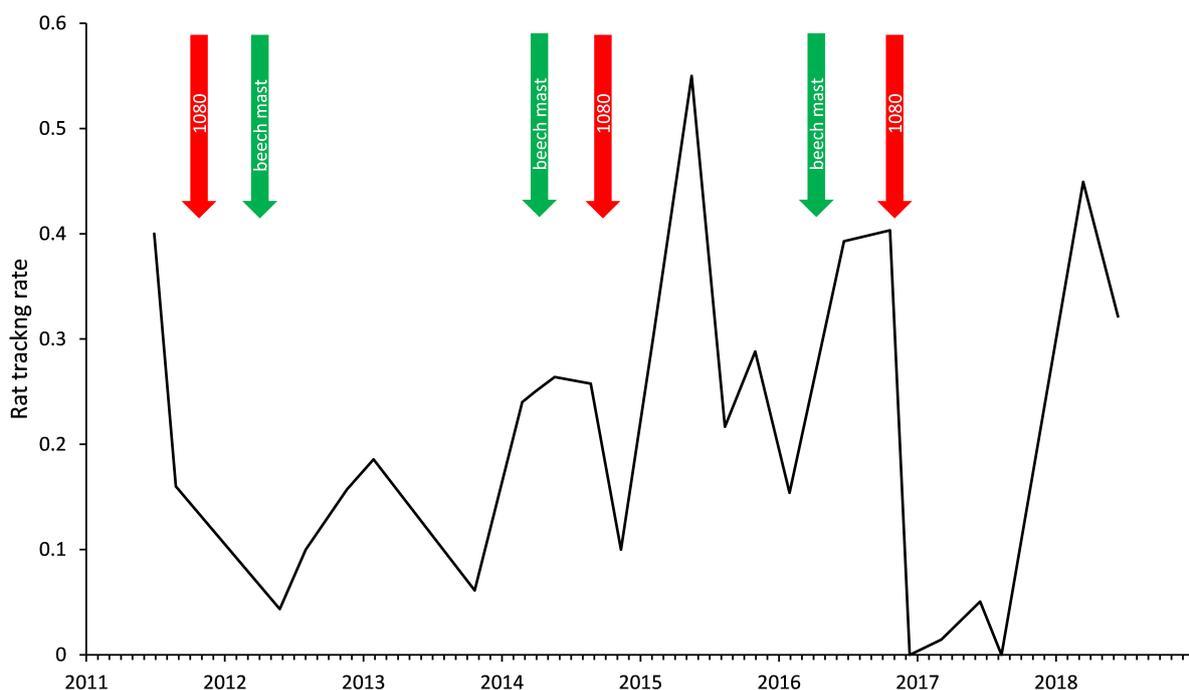


Figure 3. Rat footprint tracking rate (proportion of tunnels tracked) and timing of beech mast and aerial 1080 events in the Wangapeka/Fyfe study area, 2011–2018.

examined, models with distance to untreated land and time since 1080 and their interaction as well as season, and flood were best supported. However, the interaction between distance to untreated land and time since 1080 implausibly predicted that the recent use of 1080 increased survivorship near the edge of the treatment block but decreased survivorship in the centre of the treatment block. Furthermore, the confidence intervals of the flood coefficients were large and their inclusion in the models decreased in AICc. We have rejected river flow measures and interactions between distance and time since 1080 as useful predictors of survivorship. From this analysis we can confidently conclude that who survival is higher in the breeding season than it is during the rest of the year and that it increases further into the block (Fig. 4). The relationship between survival and distance to farmland is stronger than the relationship between survival and distance to the edge of the treatment block (Table 1).

Female who weight was best described by year and whether a transmitter was being carried (Table 2). There was considerable inter-annual variation in female who weight and

transmitters appeared to cause a weight loss of 9% per year (95% CI = 2–15%).

Probability of breeding

Of the 41 females that we recorded nesting data for, 29 were tracked for one breeding season, three were tracked for two breeding seasons, seven were tracked for three breeding seasons, and two were tracked for four breeding seasons, resulting in 64 adult-female-radio-tracking-years. Nesting attempts were detected in 34 of the 64 adult-female-years, with the proportion of females that attempted to nest ranging from 31–75% in any one year. We weighed all but eight of the females in the preceding autumn/winter with average female weights being 843 g (700–1070 g). A generalised linear model of the relationship between winter weight and probability of breeding the following spring was highly significant (deviance = 14.72, df = 1, $p < 0.001$) with heavy ducks being much more likely to breed than light ones (Fig. 5).

In our examination of the relationships between probability of breeding and year, site, and winter floods, we found no

Table 1. Model selection table for the relationship between adult female who survival and some plausible explanatory variables. Time since 1080(2) categorises time since the most recent 1080 operation into greater or less than 6 months. Distance to farmland and untreated are the distances to the nearest untrapped farmland and nearest untrapped native forest that has not been treated with 1080 for more than a year. The model selection table includes the top models with ΔAICc values less than c. 2.

Model	npar	AICc	ΔAICc	weight
distance to farmland + season	3	203.17	0.00	0.34
distance to untreated + season	3	204.28	1.12	0.20
distance to farmland + season + time since 1080(2)	4	204.39	1.22	0.19
season	2	204.82	1.65	0.15
distance to untreated + season + time since 1080(2)	4	205.17	2.00	0.13

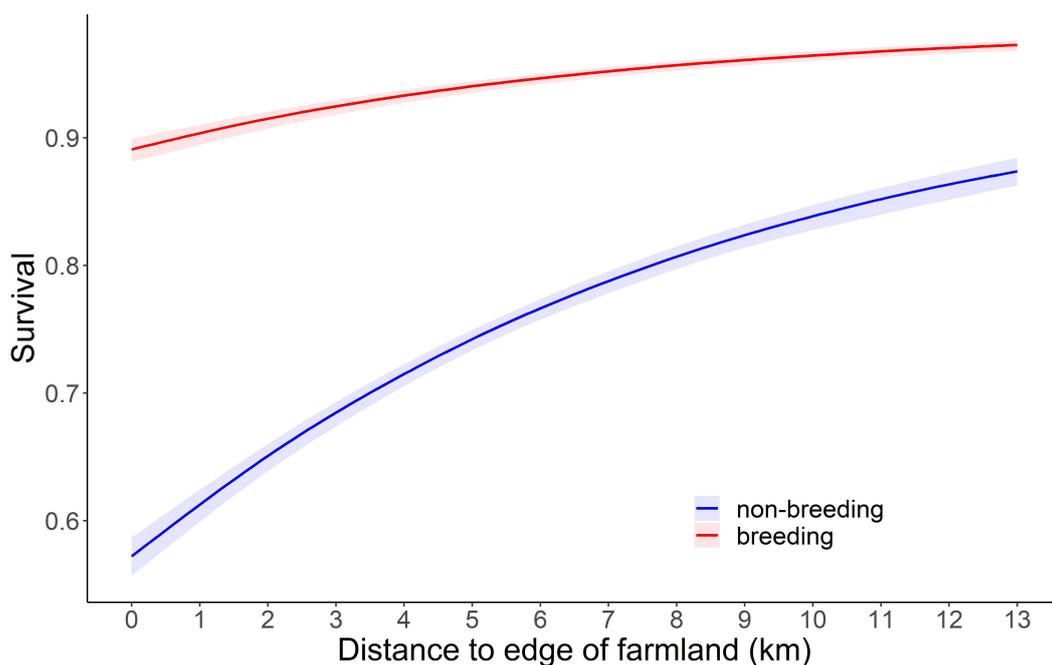


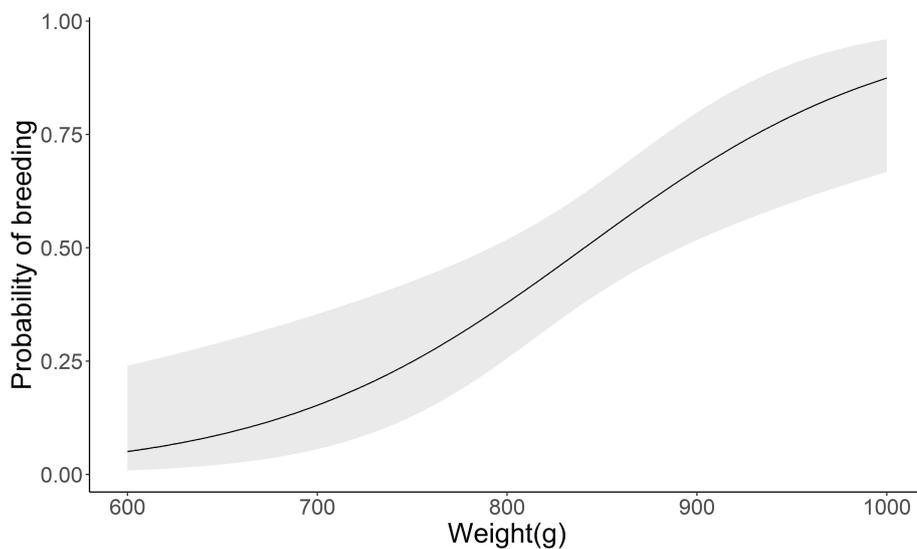
Figure 4. The relationship between who survival and distance to the edge of the farmland and breeding season. Shaded areas are 95% confidence intervals.

Table 2. Model selection table of the factors affecting adult female who weights.

Model	npar	AICc	Δ AICc	weight
year + transmitter	4	-145.57	0.00	0.70
year * transmitter	5	-143.30	2.27	0.23
year	3	-140.96	4.62	0.07
transmitter	2	-111.81	33.76	0.00
Intercept only	1	-108.44	37.14	0.00

Table 3. Model selection table examining factors (frequency of winter floods, site and year) affecting the probability of who breeding in the Wangapeka/Fyfe study area.

Model	npar	AICc	Δ AICc	weight
winter floods	2	72.28	0.00	0.74
intercept only	1	74.64	2.36	0.23
year	6	78.94	6.66	0.03
winter floods + site	11	83.86	11.58	0.00
site	11	84.13	11.84	0.00
winter floods + site	10	97.56	25.28	0.00

**Figure 5.** The relationship between winter weight and probability of breeding. Shaded area is the 95% confidence interval.

evidence of overdispersion in our most highly specified model ($\chi^2 = 23.0952$, $df = 19$, $P = 0.767$). A model with only winter floods as an explanatory variable was the best supported (Table 3), suggesting that the probability of nesting decreases with increasing frequency of floods (Fig. 6). Our data cannot tell us whether the number of winter floods was a useful predictor of female who weight with a model including floods close to the same Δ AICc as the null model (Table 4).

We detected relationships between floods and the probability of breeding, and between adult female weight and the probability of breeding, but we could not tell whether there was a relationship between floods and weight, which is probably an artefact of our small sample size.

Nesting Success

Nests contained an average of 4.9 eggs (3–7). Egg laying commenced in September or October each year, with the earliest recorded on 1 September. We determined the outcome of 40 nesting attempts, of which 28 hatched at least one egg. Stoats accounted for 33% of confirmed nest failures and weka accounted for 25%. Possums and rats visited some nests but did not prey upon any. Only one nest was inundated by flood water during the seven years of research.

Analysis of nesting success (Table 5) identified the best supported models as those including time since 1080 treatment and distance from untreated land. Nesting success was highest when within a year of a 1080 operation and when the nest was far from the edge of the treatment block (Fig. 7). Nesting

Table 4. Model selection table examining the relationship between who weight and the number of winter floods.

Model	npar	AICc	Δ AICc	weight
intercept only	2	761.70	0.00	0.66
winter floods	3	763.04	1.34	0.34

success is also possibly influenced by distance from traps (Table 5): nests close to traps might be more successful than those distant from traps. Inclusion of distance to farmland, flood, flood10, flow, and flow10 in models all increased AICc by approximately 2 (or more) AIC units and their inclusion is thus not supported.

Duckling Survival

We closely monitored 26 broods comprising 98 ducklings of which 67 (68%) survived until they fledged at about 60 days old. We monitored a further 42 duckling broods less intensively during two surveys. They comprised 171 ducklings of which 109 (64%) survived until near fledging. We monitored few ducklings that hatched more than 18 months after a 1080 operation, so only time since 1080(2) was examined for monitored broods with ducklings classified into 2 groups: < 6 months after a 1080 operation and > 6 months after a 1080 operation. We could not relate river flow data to the time of

Table 5. Model selection table examining factors affecting who nesting success. The table includes the top models with $\Delta AICc$ values less than c. 2. Time since 1080(1) is the time since the most recent 1080 operation categorised into the first 6 months after a 1080 operation, the next 6–18 months, and greater than 18 months. Time since 1080(2) categorises time since the most recent 1080 operation into greater or less than 6 months. Time since 1080(3) categorises time since the most recent 1080 operation into greater or less than 18 months. Trap and distance to untreated are the distances to the nearest trap and the nearest untrapped native forest that has not been treated with 1080 for more than a year. Flood is whether the river was in flood on the previous day and flow10 the average flow rate during the previous 10 days.

Model	npar	AICc	$\Delta AICc$	weight
distance to untreated + time since 1080(2)	3	99.05	0.00	0.20
time since 1080(2)	2	99.42	0.37	0.17
distance to untreated * time since 1080(2)	4	100.48	1.43	0.10
distance to untreated + time since 1080(2) + trap	4	100.54	1.49	0.10
distance to untreated + time since 1080(1)	4	100.59	1.54	0.09
distance to untreated * time since 1080(1)	6	100.65	1.60	0.09
time since 1080(2) + trap	3	100.68	1.63	0.09
distance to untreated + time since 1080(2) + flood	4	100.98	1.93	0.08
distance to untreated + time since 1080(2) + flow10	4	101.06	2.01	0.07

Table 6. Model selection table examining factors affecting daily duckling survival measured through intensive monitoring of broods ($n = 98$ ducklings in 26 broods). The table includes the top 10 models. Distance to farmland is the distance to untrapped farmland, time since 1080(2) is the time since the most recent 1080 operation categorised into the < 6 months after a 1080 operation or > 6 months after a 1080 operation. Flood is whether the river was in flood on the previous day. Flood10 is the number of days the river was in flood on the previous 10 days. Flow is the river flow on the previous day and flow10 the average flow rate during the previous 10 days. Age is nest age.

Model	npar	AICc	$\Delta AICc$	weight
distance to farmland x time since 1080(2) + flow	5	155.87	0.00	0.55
distance to farmland x time since 1080(2) + flow + age	6	157.81	1.94	0.21
distance to farmland x time since 1080(2) + flow10	5	158.24	2.37	0.17
distance to farmland x time since 1080(2) + flow10 + age	6	160.24	4.37	0.06
distance to farmland x time since 1080(2) + flood	5	168.30	12.43	0.00
distance to farmland x time since 1080(2)	4	170.01	14.14	0.00
distance to farmland x time since 1080(2) + flood + age	6	170.28	14.41	0.00
distance to farmland x time since 1080(2) + flood10	5	171.16	15.29	0.00
distance to farmland x time since 1080(2) + age	5	171.58	15.71	0.00
distance to farmland x time since 1080(2) + flood10 + age	6	172.98	17.11	0.00

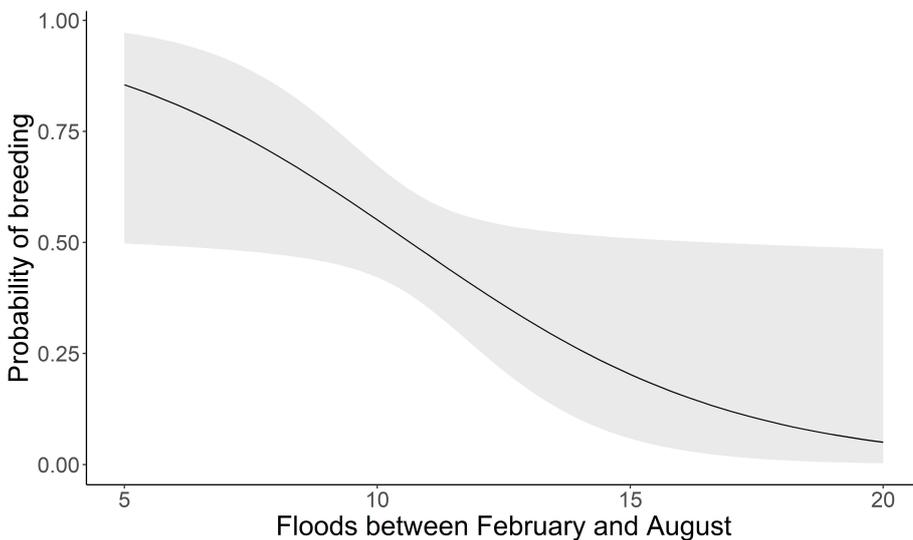


Figure 6. The relationship between the probability of a female who breeding and the number of winter floods between February and August prior to nesting. Shaded area is the 95% confidence interval.

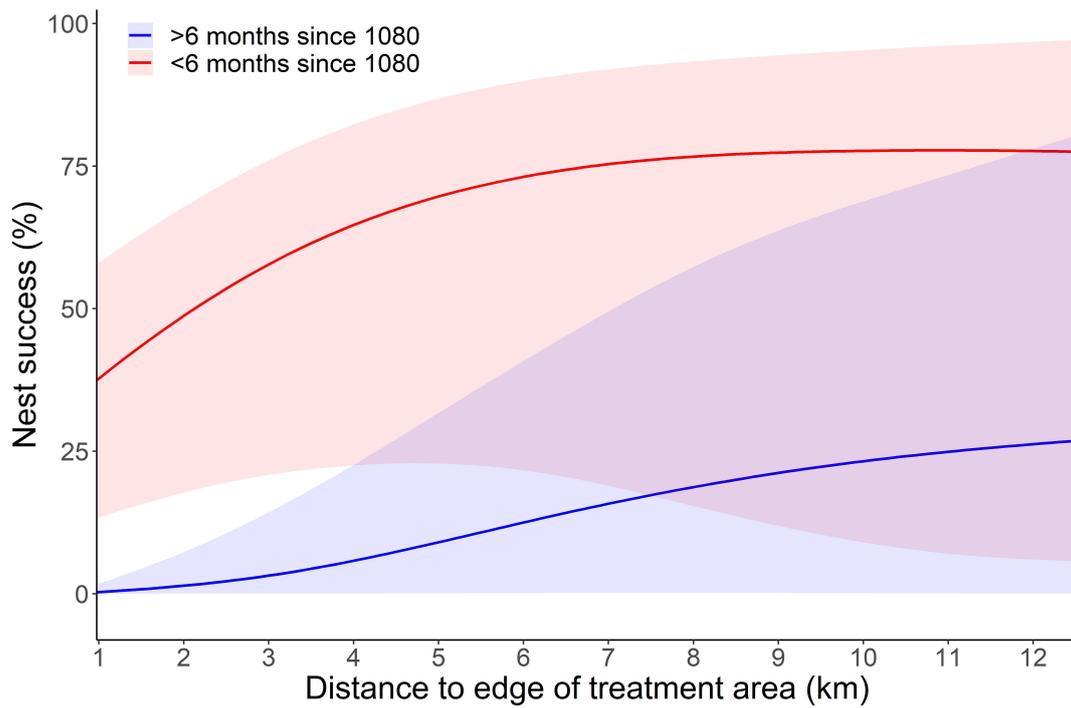


Figure 7. The effect of time since 1080 and distance to the nearest untreated native forest on nest success (from the best model in Table 5). Shaded areas represent 95% confidence intervals.

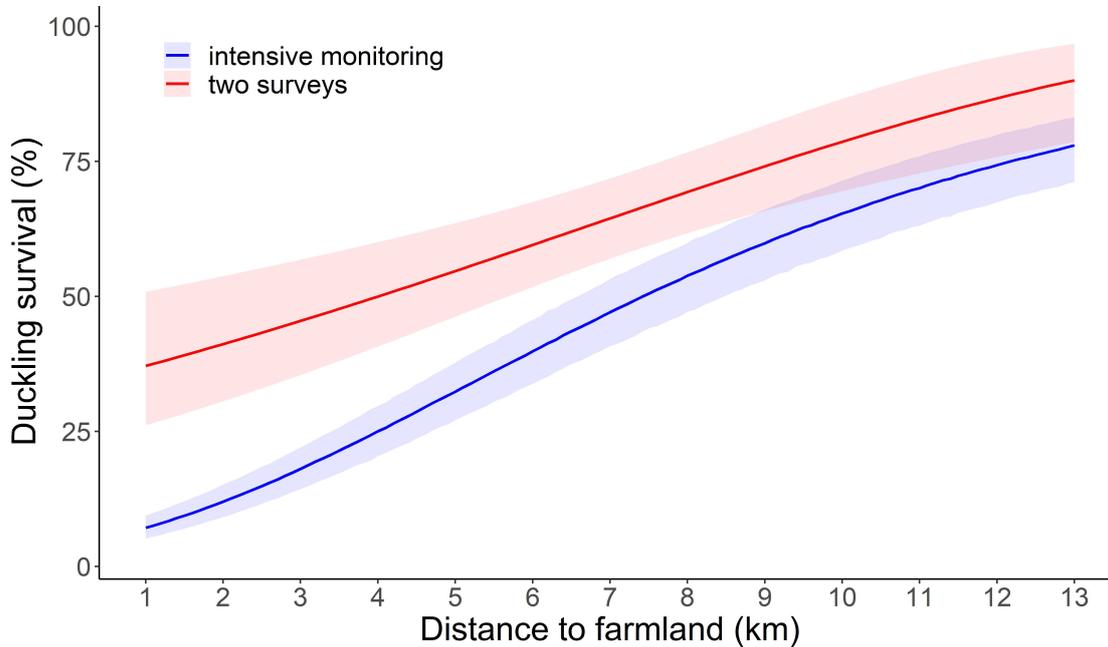


Figure 8. Modelled relationship between duckling survival and distance to farmland from intensive monitoring of ducklings and two surveys. Shaded areas are 95% confidence intervals.

disappearance of ducklings between our two surveys, so the effect of river flow was only explored with the intensively monitored ducklings. The best supported model (judged by AICc) of duckling survival in intensively monitored broods included terms for river flow, times since 1080(2) and distance to farmland and an interaction between time since 1080(2) and distance to farmland (Table 6). The best supported models (Table 7) of duckling survival between two surveys included

distance to farmland, time since 1080(2) and their interaction, but the direction of the interaction between time since 1080 and distance from farmland differed between the intensively and less intensively monitored ducklings. The inclusion in the models of a polynomial age term, any of the alternative river flow metrics, flow10, flood, and flood 10, or distance to untreated land was not well supported by the data in either dataset. We conclude that duckling survival was high under

Table 7. Model selection table of the factors affect daily duckling survival measured in the two study-area wide surveys. The table includes the top 10 models. Distance to untreated is the distance to untrapped native forest that has not been treated with 1080 for more than a year. Distance to farmland is the distance to untrapped farmland. Time since 1080(1) is the time since the most recent 1080 operation categorised into the first 6 months after a 1080 operation, the next 6–18 months, and greater than 18 months. Time since 1080(2) categorises time since the most recent 1080 operation into greater or less than 6 months. Time since 1080(3) categorises time since the most recent 1080 operation into greater or less than 18 months.

Model	npar	QAICc	Δ QAICc	weight
distance to farmland	2	59.37	0.00	0.22
distance to farmland x time since 1080(1)	6	59.40	0.03	0.21
distance to farmland + time since 1080(3)	3	59.73	0.37	0.18
distance to farmland + time since 1080(1)	4	59.99	0.62	0.16
distance to farmland + time since 1080(2)	3	60.51	1.15	0.12
Intercept only	1	64.38	5.01	0.02
time since 1080(2)	2	65.73	6.36	0.01
distance to untreated	2	65.86	6.49	0.01
time since 1080(3)	2	66.20	6.84	0.01
time since 1080(1)	3	67.31	7.94	0.00

low river flows and increased with distance to farmland (Fig. 8), but it is unclear whether it was affected by recent 1080 use. We estimated higher duckling survival with data from two surveys than from intensive monitoring, but this is almost certainly an artefact of the different methods. Two surveys will overestimate survival because some ducklings will already have died before the first survey, and some will die after the second.

Population modelling

Population parameters used in the population matrices were largely taken from the current study (Table 8). The matrix models for adult female whio in the study area predict that population growth rates are higher when both traps and 1080 are used than when only traps are used and that growth rates are higher in the interior than at the edges (Table 9). Positive population growth ($\lambda = 1.01$) was predicted only near the centre of the study area (c. 13 km from the edge) with both traps and 1080.

Discussion

The use of low-intensity stoat control has been shown to significantly increase whio nesting success in Fiordland, New Zealand (Whitehead et al. 2008). Our research shows that the pulsed application of aerial 1080 in a low-intensity trapping area in a beech dominated forest system provided greater protection to whio nests in the year of 1080 than trapping alone.

This study also revealed a positive relationship between distance into the interior of the treatment block and whio population growth, nesting success, duckling, and adult survival. Nest success was higher and adult, and duckling, mortality lower in the interior of the block. Nest success was more closely related to the distance to the edge of the treated native forest than it was to distance to farmland, and time since 1080 greatly affected the relationship. This pattern is most likely the result of gradual migration of stoats back into the trapped and poisoned area following 1080 operations. In contrast, adult and duckling survival were more closely related to distance from farmland and there was no clear effect of 1080. Two possible explanations for high survival further into the block are possible. In our study the streams and rivers further into the block were smaller than those near the edge, and duckling survival is greatly affected by floods. Ducklings in small streams and rivers might have a higher chance of surviving floods than ducklings in large streams and rivers. Alternatively, it is possible that cats (*Felis catus*) and ferrets (*Mustela furo*) are more common on farmland where there are rabbits (*Oryctolagus cuniculus*) than they are in native forest (Garvey & Byrom 2021; Gillies & van Heezik 2021) and they may be responsible for duckling and adult mortality near the edge of the farmland.

Although we detected a relationship between 1080 use and nesting success, we were unable to detect any effect of 1080 use on adult survival, even though a relatively large number of our monitored adults were preyed upon. This result suggests that adult females are less susceptible to predation than are nests and that the effect of our spring 1080 operations did not last long enough to protect adult females in the non-breeding period: the period when they were most susceptible to predation.

Whitehead et al. (2008) showed that the population trajectory of whio in Fiordland improved from rapidly declining to slowly declining when low intensity trapping was applied. In the Wangapeka/Fyfe, aerial 1080 provided an additional boost to nest success, which our modelling suggests might facilitate population increase, but only near the centre of our treatment block. Estimated population growth rates in the Wangapeka/Fyfe at the edge of our treatment block ($\lambda = 0.60$ and 0.63 , with and without aerial 1080, respectively) were lower than in the Fiordland study ($\lambda = 0.95$) (Whitehead et al. 2010). In the centre of our treatment block, population growth rates when trapping occurred but without 1080 ($\lambda = 0.95$) were similar to those in Fiordland also without 1080, while in the centre of the Wangapeka/Fyfe block and with both traps and 1080, the population trajectory shifted to slowly increasing ($\lambda = 1.01$). Kemp et al. (2018) noted the importance of extensive natural barriers (ocean and/or permanent ice/snow) to reinvasion by predators in prolonging the period of stoat suppression and improving kea nest survival after a 1080 operation at Okarito. The Whitehead et al. (2008) whio study site in Fiordland is bounded by tall, steep mountains, a lake, and a fiord, and reinvasion by stoats is likely to be much slower than in the Wangapeka/Fyfe, which is bounded by lower mountains and farmland. Thus, the differences in population parameters observed between the Wangapeka/Fyfe and Fiordland are consistent with the Fiordland study site having trapping but no 1080, and being more difficult for stoats to reinvade. Beath (2010) also observed whio population growth in an integrated pest control site in Tongariro Forest where a continual increase in number of pairs occurred over a six-year period and female survival was highest in the year when both trapping and aerial 1080 occurred. Beath's (2010) study site differed from ours in

Table 8. Parameters used in matrix models. Source 1 = this study, source 2 = Whitehead et al. (2010). Block centre was defined as 13 km from edge.

Parameter	Stoat trapping		Stoat trapping and 1080		Source
	Block edge	Block centre	Block edge	Block centre	
Eggs/brood	4.909	4.909	4.909	4.909	1
Proportion of adult females breeding each year	0.531	0.531	0.531	0.531	1
Nest survival from laying to hatching	0.005	0.235	0.396	0.636	1
Duckling survival from hatching to fledging	0.210	0.692	0.210	0.692	1
Juvenile survival from fledging to 1 year old	0.510	0.510	0.510	0.510	2
Annual female survival	0.595	0.862	0.595	0.862	1

Table 9. Estimated adult female whio population growth rates (λ) (and 95% confidence intervals) with traps, and traps and 1080, and near the edge of the block and in its interior.

	Traps only	Traps and 1080
Edge of block	0.60 (0.58–0.61)	0.63 (0.60–0.66)
Centre of block	0.95 (0.86–1.13)	1.01 (0.88–1.13)

that it was dominated by regenerating mixed broadleaf forest and water was abstracted for power use, but it showed the value of integrated pest control for enhancing a whio population.

Although simulation models such as ours can be useful tools for exploring ‘what-if’ scenarios, they are often not good predictors of the trajectories of real populations (Caswell 2001). They cannot predict, for example, what happens when conditions change dramatically, and in this case, they are based on small sample sizes. The real test of our pest control regime comes from long-term population monitoring (since 2003), which shows that whio population growth in our study area has been more rapid than predicted by our population model, especially since 2017 when monitoring shows almost a doubling in pair number from 43 pairs to 79 pairs in 2021 (KS unpubl. data). The Wangapeka/Fyfe has had a long-term Whio Operation Nest Egg (WHIONE) programme in which captive raised juveniles are regularly released into the site which has undoubtedly contributed to the population increase.

There was no evidence that any whio in this study died from 1080 poisoning, a result that is reflected in studies at other whio management sites (Veltman et al. 2014; Fairweather et al. 2018). Veltman et al. (2014) noted that there is a small risk that individual whio will die from 1080 poisoning.

We detected substantial weight-loss among adult females carrying back-pack transmitters, but we were unable to determine whether this led to increased mortality because almost all the birds we monitored carried transmitters. Heavier females were more likely to attempt to nest, and females weighing more than 840 g in late autumn had a greater than 50% probability of nesting in the following breeding season. Other studies have noted that the condition of the adult female bird has significant effects on whether they breed. Harper et al. (2006) hypothesised that there is a minimum weight threshold below which female kakapo (*Strigops habroptilus*) are incapable of nesting. Chastel et al. (1995) noted that former breeders that skip a season could have experienced low foraging success before the breeding season and may not have acquired sufficient reserves to invest in reproduction. In

our study, we found that the probability of nesting increased if there were fewer floods, and therefore presumably greater river stability and increased food supply, in the six months before the breeding season. Productivity of rivers in New Zealand is known to vary with flow rate; the more frequently a river floods, the lower its productivity (Clausen & Biggs 1997). Reduced weight and body condition in female whio wearing back-pack transmitters could make the negative effects of flooding more pronounced and hence reduce their likelihood of nesting. Rotella et al. (1993) found that female wild mallards (*Anas platyrhynchos*) wearing harnessed backpacks initiated fewer nests than birds fitted with implants. We recommend that back-pack transmitters are used on whio with caution. It is not possible to predict the frequency or duration of flood events leading up to a whio breeding season but given that the weight of females at the start of the breeding season could indicate a high or low nesting rate, monitoring weights may allow managers to predict whether intensifying integrated pest control would be worthwhile to maximise whio productivity.

Duckling survival in the Wangapeka/Fyfe decreased with higher flows and Whitehead et al. (2008) also recorded that small ducklings frequently disappeared at times of high-water flow suggesting that flood events contribute to duckling mortality. Williams (1991) and Beath (2010) also suggested that the disappearance of ducklings was likely related to flood events. The remains of whio ducklings are rarely found and like Whitehead et al. (2008), we suggest that it is not possible to quantify the impacts of predation on this life history stage. Interestingly, this study indicates that where effective integrated pest control is in place, floods are the next biggest threat to whio productivity. Simpkins et al. (2015) suggested a similar result where they found that whio in the Te Urewera Mainland Island faced a heightened risk of extinction if the frequency of severe flooding increased significantly without a corresponding intensification of predator management.

Other than on flow-regulated rivers, we cannot control flooding, so it seems sensible that in the future whio management in beech forest is focused on integrated pest control, and treatment block size is considered. In the centre of blocks at least as large as our study block ($\geq 40\,000$ ha), a combination of traps and 1080 should be sufficient for long-term population persistence of whio. However, in smaller blocks, integrated control may be insufficient to secure whio populations. It is also likely that in large ($> 100\,000$ ha), or remote treatment blocks, 1080 alone may be enough to protect whio; this is currently under investigation by the Nelson-based DOC Threats Unit.

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Author contributions

KS conceptualised the study and together with GE and JM, designed the study. KS wrote the manuscript, to which all authors contributed revisions and refinements. KS, JM and RD carried out the data collection. Formal analysis was carried out by GE.

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