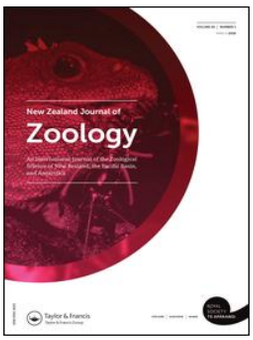

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RESEARCH ARTICLE

Do mallard ducks feature in the diet of stoats in an agricultural landscape?

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ABSTRACT

Research on stoat diet composition in New Zealand has primarily focussed on consumption of indigenous fauna in largely unmodified landscapes. This study used stomach content and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analysis to assess stoat diet in a highly modified agricultural landscape in Southland, New Zealand, focussing on stoat predation of the mallard duck. Stoats were captured in Lochiel, Southland during August–November 2016 and 2017. Stomach content analysis of 26 captured stoats revealed limited stoat predation of mallards ($n = 1$) and mallard eggs ($n = 1$). Using liver tissue, stable isotope mixing models suggested that bird eggs on average met between 73 and 85% of stoat metabolic requirements throughout the mallard breeding period. Furthermore, mixing model outputs suggested that bird eggs made up a substantial proportion (77–84%) of stoat assimilated diet early in the mallard breeding period, when mallard eggs are readily available. In contrast, isotope mixing models suggested that mallard ducks/ducklings did not make a large overall contribution to stoat diets (< 3%). This study shows that stoats are an egg predator in the Southland agricultural landscape and mallard eggs may contribute to stoat assimilated diet early in the mallard breeding season before alternative prey items become available.

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Introduction

Introduced mammalian predators have been implicated in the decline of biodiversity worldwide (Blackburn et al. 2004; Doherty et al. 2016; Russell et al. 2016). In New Zealand, rats (*Rattus norvegicus*), cats (*Felis catus*), stoats (*Mustela erminea*), weasels (*Mustela nivalis*), mice (*Mus musculus*), ferrets (*Mustela furo*) and possums (*Trichosurus* vulpecula) were introduced from 1769 and have contributed to significant declines in endemic wildlife (King 2005; Wright 2017). Stoats have been identified as a predator of native fauna in forest (King and Moody 1982; Murphy and Dowding 1995), wetland (O'Donnell et al. 2015), alpine (Smith et al. 2005; McAulay 2019) and braided riverbed habitats (Murphy et al. 2004; Dowding et al. 2015).

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In the agricultural plains near Lochiel (Southland), stoats are the most abundant mustelid (Southland Fish and Game, unpublished data) and whilst non-native avifauna and mammals are common, native avifauna are uncommon (pers. obs.). Common potential stoat prey items near Lochiel include non-native passerines, rodents, lagomorphs and Anseriformes, specifically, the mallard duck (*Anas platyrhynchos*). Predation of mallard hens and their ducklings and eggs is concerning for recreational gamebird hunters, waterfowl enthusiasts and Fish & Game New Zealand, the statutory managers of gamebird populations.

In New Zealand, mallards can initiate nests as early as mid-July, and will re-nest multiple times if their nest fails (Sheppard et al. 2019). The peak mallard nesting period is late August to September with the peak brood rearing period being September through to November (Sheppard 2017; Sheppard et al. 2019). Recent research in Waikato and Southland has revealed that some mammalian and avian species prey on nesting mallard hens, ducklings and eggs (Sheppard 2017). Radio tracking of 304 mallard hens revealed at least one depredation event occurred at 167 (39%) of 432 monitored nests, with unidentified predators removing or destroying all eggs from 18% of nests (Sheppard 2017). Furthermore, duckling survival rangedg from 16-30% and of 243 hens with internal transmitters, 21 (9%) were killed by predators whist nesting (Sheppard 2017). These predation and survival rates are of concern for Fish & Game New Zealand because some New Zealand regions are experiencing declining mallard populations (McDougall and Amundson 2017) and gamebird licence sales.

Both within New Zealand and internationally, stoats exhibit a wide dietary niche (King and Moody 1982; Alterio and Moller 1997; McDonald et al. 2000; Remonti et al. 2007) and will opportunistically exploit temporally available food sources (King 1983; Remonti et al. 2007; Smith et al. 2011). For gamebird managers the potential for opportunistic stoat predation on seasonally abundant food sources is concerning, because from August through to late-November mallard nests and ducklings (Garrick et al. 2017; Sheppard et al. 2019) may provide a temporal food source for stoats. Mallards typically nest on the ground within narrow, linear, unmanaged habitat (rank grass, shelterbelts) (Garrick 2016; Sheppard 2017). These habitat features are common foraging areas for stoats and feral cats in agricultural areas of Southern New Zealand (Alterio et al. 1998) and the ground nesting behaviour of mallards may make their nests particularly vulnerable to mammalian predators.

To date, studies on the foraging ecology of New Zealand stoats have used gut content analysis to infer diet and have focussed primarily on stoat predation of native fauna in intact forest, alpine, and riverbed habitat (King 1983; Murphy et al. 2004; Smith et al. 2005; Smith et al. 2008; Dowding et al. 2015). In this study, complementary stomach content and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analysis was used to assess stoat diet in a highly modified agricultural landscape with the focus being predation of a nationally valued gamebird (Nugent 1992; Stewart and Garrick 2017). Using a dual stomach content and stable isotope approach can provide greater insight into the assimilated diet of a consumer because different tissue types have different isotopic turnover rates (days–months) (Tieszen et al. 1983; Vander Zanden et al. 2015). Typically, metabolically active tissues like liver have a faster turnover rate relative to less metabolically active tissues such as hair (Tieszen et al. 1983; Vander Zanden et al. 2015).

The aim of this study was to determine the extent to which mallard ducks, ducklings and eggs are consumed by stoats. This will help inform managers of the risk that stoats pose to mallards. Given the extent of mallard hen, duckling and nest predation observed in recent studies, it was hypothesised that mallards and mallard eggs would feature heavily in the diet of stoats during the mallard nesting and brood rearing period indicating that stoats are exploiting this seasonally abundant food source.

Materials and methods

Study area

Stoat trapping was conducted near Lochiel, Southland (46°11'36.87"S, 168°17'53.88"E). Surrounding land use consisted of intensive agriculture, specifically dairy cattle and sheep farmed on predominantly rye grass (*Lolium perenne*) pastures. The study area was exclusively private land scattered with several small (<1 ha) man-made ponds created for waterfowl habitat or to hold livestock waste (effluent ponds). The Oreti River lies to the west of the trapping site between 230 m – 3.6 km away, and numerous small streams and agricultural drains are scattered throughout the study area. The remaining land cover was limited to road verges or ditches of rank grass and shelterbelts of typically macrocarpa (*Cupressus macrocarpa*), gum tree (*Eucalyptus* spp.) or flax (*Phormium tenax*).

Stoat trapping

Stoat trapping was conducted in 2016 and 2017 between 8 August and 30 November; this coincided with the main mallard nesting and brood rearing period (Sheppard 2017). Stoats were trapped and killed using paired Mark IV Fenn traps set at either end of a wooden tunnel (length 800 mm, width 220 mm, height 180 mm). In the 2016 season, tunnels were baited with 20 g pieces of fresh rabbit, nailed to the roof of the trap tunnel. Towards the end of the 2016 season baits were changed to non-estrous female or adult male stoat bedding to try and lessen hedgehog (*Erinaceus europaeus*) bycatch. During the 2017 trapping season, non-estrous female and adult male stoat bedding was used exclusively to bait the traps.

Traps were placed along habitat features such as hedgerows, shelter belts and woodlots as anecdote suggests stoats may use these linear features as movement corridors. Traps were inconsistently spaced, ranging from 80 m – 1.2 km apart. Traps were checked every three or four days. Captured stoats were placed in labelled plastic bags and frozen for later analysis.

Prey source collection

Likely stoat prey sources were harvested from the study area for stable isotope analysis and included: adult mallard hens, mallard ducklings, mallard eggs, passerines (blackbirds (*Turdus merula*), song thrush (*Turdus philomelos*), common starling (*Sturnus vulgaris*)), passerine eggs, lagomorphs (European hares (*Lepus europaeus*), rabbits (*Oryctolagus cuniculus*)) and rodents (Norway rats and house mice) (King 2005).

Mallard hens from the study area were harvested with a shotgun at the end of the game-bird season (late July) ($n = 4$) or opportunistically as fresh roadkill during the breeding season ($n = 4$). Blackbirds ($n = 2$), thrushes ($n = 3$) and starlings ($n = 2$) that were caught as trap bycatch or freshly killed by vehicles were collected throughout the study period. Five passerine eggs were collected from five separate nests within the study area (blackbird egg $n = 1$, starling egg $n = 2$, thrush egg $n = 2$). European hares ($n = 3$) and common rabbits ($n = 2$) were either harvested as fresh roadkill or caught as bycatch in our trapping tunnels. Rats were caught as bycatch in the stoat trapping tunnels ($n = 4$) and mice were trapped using Victor® wooden mouse traps ($n = 3$). Freshly laid mallard eggs ($n = 5$) were harvested from five separate nests. Mallard nests were located using an indicating bird dog. Three class 1a ducklings and two class 1c ducklings (Gollop and Marshall 1954) were harvested by hand from within the study area. An invertebrate isotopic signature was not determined in this study as there was uncertainty about invertebrate availability as a prey item. Following the collection of the prey items, small pieces of muscle tissue were cut from the prey sources and frozen in labelled bags. Breast tissue was taken from the small birds and mallard hens whilst tissue from the hind legs was taken from all other prey items.

Stomach and stable isotope analysis

Trapped stoats had the contents of their stomachs and intestines removed for analysis. Using a dissecting microscope, stomach contents were identified visually by comparison with hair, feathers and shell fragments of known origin. Prey items were grouped according to the prey categories: mallard duck, mallard egg, small bird (passerines), small bird egg, lagomorph, rodent, vegetation, invertebrate, unidentified tissue and unidentified hair.

Following stomach content analysis, the liver was removed from each stoat for later determination of $\delta^{15}N$ and $\delta^{13}C$. Although the isotopic turnover rates of stoat liver have not been determined, liver was the elective tissue because in general it is a fast-turnover tissue, representing the average diet several days before an animal's death (Dalerum and Angerbjörn 2005). Stoat liver, prey muscle tissue portions, mallard eggs (homogenised yolk and albumen) and small bird eggs (homogenised yolk and albumen) were individually dried at 70°C for 72 h. Following drying, stoat and prey tissue samples were individually ground with a mortar and pestle and placed in labelled 2 mL ependorff tubes. Before stable isotope analysis, lipids were extracted from stoat liver tissue, mallard eggs and small birds eggs with a 2:1 chloroform:methanol solution (Bligh and Dyer 1959). Lipids were extracted from these tissues because of high (>4) C/N ratios indicative of significant lipid content and because no suitable lipid normalisation equations were available (Ehrich et al. 2011). The C/N ratio of all muscle tissue was > 4, so lipid content in all prey muscle tissue was arithmetically corrected using a general mammal/bird specific lipid normalisation equation (Ehrich et al. 2011, Equation 3). Lipid normalisation equations provide an economic and convenient way to account for lower $\delta^{13}C$ values because of lipid content whilst preserving $\delta^{15}N$ integrity (Post et al. 2007; Ehrich et al. 2011). Samples for carbon and nitrogen isotope analysis were prepared by weighing 0.8 mg (± 0.08) samples of homogenised material into tin foil capsules and dried under vacuum overnight. Nitrogen and carbon isotopes were assayed by combusting whole material to N_2 and CO_2 gas in a Carlo Erba NC2500 elemental analyser (CE Instruments,

Milan), using helium carrier gas enriched with oxygen. The gases were separated on a packed Porapak QS GC column and sent sequentially to the inlet of a Europa Scientific '20/20 Hydra' (Europa Scientific, UK) isotope ratio mass spectrometer (IRMS), in continuous flow mode. Raw isotope ratios were normalised by three-point calibration to international scales using two IAEA (International Atomic Energy Agency) reference materials (USGS-40 and USGS-41) and a laboratory standard (EDTA-OAS), assayed with the unknown samples. $\delta^{13}C$ and $\delta^{15}N$ values of these standards are as follows: USGS-40 (−4.52, −26.24), USGS-41 (−47.57, −37.76), EDTA-OAS (−0.73, −38.52). Samples were processed at the Isotrace lab at the University of Otago, Dunedin, New Zealand.

The laboratory standard, EDTA-OAS (Elemental Microanalysis Ltd, UK) has multi-year and multi-laboratory calibration records against IAEA reference materials. EDTA-OAS was also used as a drift control material by assaying a pair of aliquots after every twelve samples of a batch. Instrumental drift corrections (when applied) were calculated from regression of the EDTA-OAS against time. Precision was assessed from the RMS difference between sequential duplicates (IANZ 2004) of every 10th sample by random inclusion of three true control materials chosen to mimic the nature of the sample materials. Expected precision for analysis of control materials is typically ± 0.2 ‰ for $\delta^{15}N$ and ± 0.1 ‰ for $\delta^{13}C$. Isotopic ratios are then expressed as parts per thousand using the formula:

$$\delta X(‰) = \left(\frac{\text{Rsample}}{\text{Rstandard}} - 1\right) \times 1000$$

where δX is $\delta^{15}N$ or $\delta^{13}C$, and R is the respective $^{15}N/^{14}N$ or $^{13}C/^{12}C$ ratio or the sample being measured.

Data exploration

Prior to the development of mixing models, an isospace plot was produced and visually inspected to (1) confirm that consumer $\delta^{15}N$ and $\delta^{13}C$ values fell within the prey polygon in isospace (Ben-David and Flaherty 2012), (2) that prey and consumer sampling was sufficient and appeared biologically reasonably (Stock et al. 2018) and (3) to determine whether isotopic signatures of the prey groupings were sufficiently dissimilar (a criteria for the effective use of isotope mixing models (Phillips et al. 2014)). Where required, prey types were intuitively grouped (or 'lumped') with attention to retain biological meaning within the aggregated source (Stock et al. 2018). Students t-tests were used to confirm that $\delta^{15}N$ and $\delta^{13}C$ values differed among grouped samples (Zar 2010). A Holm adjustment was applied to *P* values to account for multiple comparisons (Holm 1979). Data analysis was carried out in R version 3.2.1.

Isotope mixing model

Stable isotope data were analysed using Bayesian isotope mixing model package MixSIAR (Stock and Semmens 2016) in the programme R (R Core Team 2017). An individual model was produced for each stoat. Informative priors were added to each model because they improve the accuracy of the mixing models and reduce the confidence

intervals of dietary estimates, especially where prey categories are closely spaced or linearly aligned within the isospace (Moore and Semmens 2008; Derbridge et al. 2015). Informative priors were constructed using the percentage frequency of occurrence of each prey category, taken from stomach contents of the stoats caught in this study. To avoid an overly-informative alpha prior based on a small sample size (i.e. a limited number of stoat stomachs) informed priors were scaled to the weight of an uninformative prior, using the following formula:

$$\alpha = \frac{\text{proportion of diet from prey category} * \text{number of prey categories}}{\text{total number of samples from all categories}}$$

Mixing models produce the most reliable results when prey categories are pooled into broad categories of easily identified items within the stomach contents (Phillips et al. 2014). This pooling yields greater certainty from model estimates and narrower confidence intervals (Phillips 2012). Additionally, isotopically distinct prey items are criteria for the use of mixing models (Phillips et al. 2014). After data exploration (evaluating the position of prey sources in isospace), prey items were lumped into five prey categories, easily identified in stoat stomachs: lagomorph, rodent, small bird, mallard, and bird egg.

When applying the isotope mixing model, stoat specific $\delta^{15}N$ and $\delta^{13}C$ trophic enrichment factors (TEFs) were not available so the TEFs determined by Roth and Hobson (2000) for adult red foxes (*Vulpes vulpes*) were used. A TEF of 3.4‰ (0.06 SEM) was applied for $\delta^{15}N$ and 0.4‰ (0.063 SEM) for $\delta^{13}C$.

Results

Stomach content analysis

Twenty-six stoats (2016 $n = 12$, 2017 $n = 14$) were caught at the Lochiel study site during the mallard breeding period and their stomach contents were analysed (Table 1). Prey remains were found in all captured stoats. The eggs of small birds were the most frequently encountered prey item. Mallard feathers and tissue was found in one stoat and mallard egg was found in another stoat. For seven of the captured stoats the stomach contents could not be identified because the contents were too digested and did not exhibit remnants of feathers, hair, eggshell or invertebrate.

Table 1. Frequency and percent frequency of occurrence for prey items found in the stomachs of 26 stoats caught in Lochiel, Southland, New Zealand between 14 August and 24 November 2016 and 2017.

Prey item	Frequency	Percent frequency (%)
Mallard	1	3.8
Mallard egg	1	3.8
Small bird	7	26.9
Small bird egg	8	30.7
Rodent	4	15.4
Unidentified tissue	7	26.9
Unidentified hair	3	11.5
Invertebrate	1	3.8
Vegetation	6	22.2
Lagomorph	0	0

Stable isotopes and mixing model

All stoat liver $\delta^{15}N$ and $\delta^{13}C$ signatures, corrected by the trophic enrichment factors, fell within the prey polygon in isospace i.e. the space defined by the measured prey values (Figure 1). This indicated good support to continue the proposed modelling approach (Smith et al. 2013). Stoat liver $\delta^{15}N$ signatures ranged from 10.6‰ to 13.5 ‰ while $\delta^{13}C$ signatures ranged from −27.2‰ to −24.7 ‰ (Table 2).

Five prey categories were formed as inputs for our isotope mixing model, - mallard (included mallard hen and duckling tissue), small birds, rodent (rats and mice), egg (mallard egg and small bird egg) and lagomorph (rabbit and hare) (Appendix 1). The mean $\delta^{13}C$ value of rodents did not differ significantly from mallards, bird eggs or small birds (multiple comparison Holm test, $P > 0.05$, $n = 10$). However, the mean $\delta^{15}N$ value of rodents did differ significantly from mallards, bird eggs and small birds (Holm test, $P < 0.05$, $n = 3$) which allowed for segregation amongst prey species in isospace. The $\delta^{15}N$ and $\delta^{13}C$ values for male and female stoats did not differ significantly ($\delta^{15}N$, male mean (SEM) = 12.1±(0.2), female mean (SEM) = 12.2±(0.2), $t = 0.28$, d.f. = 24, $P = 0.78$) ($\delta^{13}C$, male mean (SEM) = −26.4±(0.3), female mean(SEM), −25.9±(0.1) $t = 1.45$, d.f. = 24, $P = 0.16$).

Bird eggs were identified by our mixing models as the most important prey item, meeting on average between approximately 73 and 85% of stoat metabolic requirements throughout the mallard breeding period (Table 3, supplementary material (Figure S1)). However, the posterior distributions of prey categories 'bird eggs' and 'small birds' have

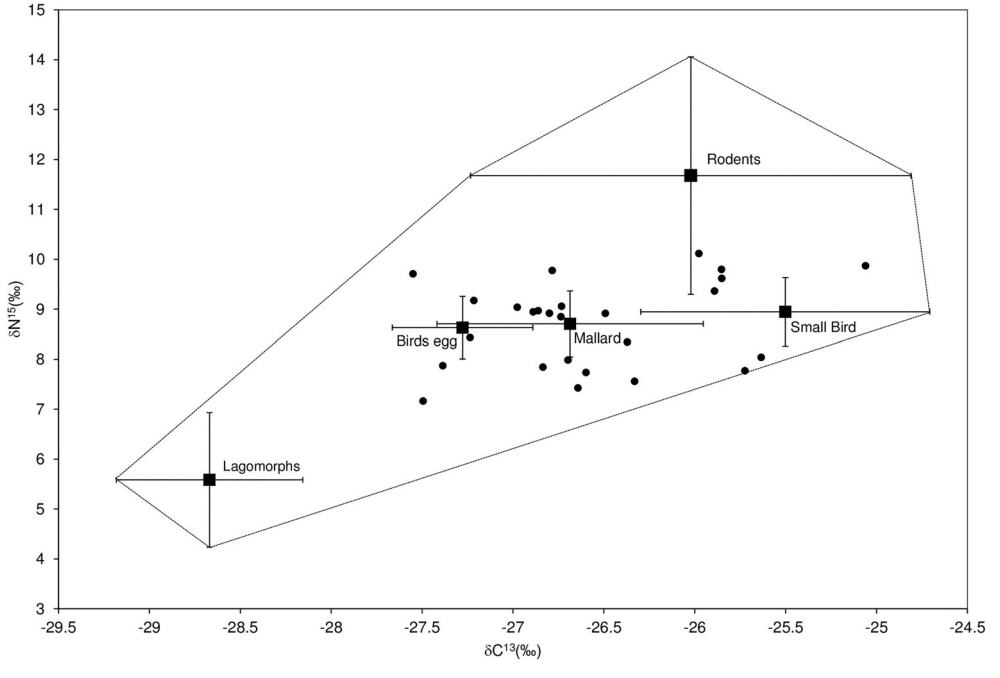

Figure 1. Isospace plot showing $\delta^{13}C$ and $\delta^{15}N$ values of stoat livers taken in Lochiel, Southland, in relation to their prey. Values are means ± 1 standard deviation for prey values. Stoat liver values have been corrected using tissue specific trophic enrichment factors.

Table 2. Stable isotope values ($\delta^{15}N$, $\delta^{13}C$) of stoat liver tissue where stoats were captured between 14 August and 24 November 2016 and 2017 in Lochiel, Southland, New Zealand. Values for stoat liver are from lipid extracted tissue.

Stoat sex	Date of capture	$\delta^{15}N^{Liver}$	$\delta^{13}C^{Liver}$
Female	5/09/2016	12.6	−26.8
Male	5/09/2016	13.2	−26.4
Male	7/09/2016	12.5	−26.3
Male	19/09/2016	12.3	−26.4
Female	22/09/2016	12.3	−26.3
Female	22/09/2016	11.8	−26.9
Female	29/09/2016	13.2	−25.5
Female	3/10/2016	11.3	−27.0
Male	4/10/2016	13.1	−27.2
Male	21/10/2016	10.8	−26.2
Female	22/10/2016	11.1	−26.2
Male	31/10/2016	12.4	−26.5
Female	14/08/2017	13.5	−25.6
Male	11/09/2017	11.4	−26.3
Male	19/09/2017	10.6	−27.1
Male	3/10/2017	13.0	−25.5
Male	9/10/2017	12.4	−26.5
Male	11/10/2017	11.7	−26.0
Male	16/10/2017	12.3	−26.1
Male	24/10/2017	12.4	−26.6
Male	24/10/2017	11.0	−25.9
Female	8/11/2017	11.4	−25.2
Male	8/11/2017	11.2	−26.4
Male	13/11/2017	12.8	−25.5
Female	13/11/2017	13.3	−24.7
Female	24/11/2017	11.2	−25.3

Table 3. Estimated dietary proportions for individual stoats caught during the 2016 and 2017 mallard breeding season at Lochiel, Southland, New Zealand. Values are means ± 1 SD.

Sex	Date of capture	Mallard	Small bird	Bird egg	Rodent	Lagomorph
Female	5/09/2016	0.022 ± 0.067	0.074 ± 0.097	0.84 ± 0.156	0.053 ± 0.075	0.011 ± 0.055
Male	5/09/2016	0.025 ± 0.073	0.082 ± 0.105	0.819 ± 0.171	0.066 ± 0.093	0.009 ± 0.043
Male	7/09/2016	0.026 ± 0.076	0.825 ± 0.159	0.082 ± 0.097	0.057 ± 0.078	0.01 ± 0.048
Male	19/09/2016	0.025 ± 0.075	0.081 ± 0.096	0.83 ± 0.157	0.054 ± 0.071	0.01 ± 0.049
Female	22/09/2016	0.027 ± 0.08	0.081 ± 0.095	0.828 ± 0.158	0.053 ± 0.07	0.011 ± 0.052
Female	22/09/2016	0.023 ± 0.069	0.071 ± 0.088	0.847 ± 0.149	0.046 ± 0.061	0.013 ± 0.063
Female	29/09/2016	0.029 ± 0.083	0.105 ± 0.132	0.779 ± 0.2	0.08 ± 0.112	0.007 ± 0.035
Female	3/10/2016	0.02 ± 0.056	0.065 ± 0.08	0.856 ± 0.149	0.042 ± 0.057	0.017 ± 0.082
Male	4/10/2016	0.021 ± 0.072	0.07 ± 0.101	0.841 ± 0.17	0.058 ± 0.095	0.01 ± 0.051
Male	21/10/2016	0.021 ± 0.063	0.07 ± 0.083	0.849 ± 0.152	0.043 ± 0.06	0.016 ± 0.073
Female	22/10/2016	0.023 ± 0.071	0.074 ± 0.09	0.843 ± 0.152	0.045 ± 0.06	0.014 ± 0.064
Male	31/10/2016	0.025 ± 0.074	0.079 ± 0.095	0.833 ± 0.155	0.053 ± 0.072	0.01 ± 0.047
Female	14/08/2017	0.028 ± 0.083	0.099 ± 0.128	0.779 ± 0.203	0.087 ± 0.123	0.007 ± 0.034
Male	11/09/2017	0.024 ± 0.072	0.076 ± 0.094	0.839 ± 0.154	0.047 ± 0.062	0.014 ± 0.063
Male	19/09/2017	0.017 ± 0.05	0.058 ± 0.078	0.861 ± 0.164	0.039 ± 0.063	0.024 ± 0.106
Male	3/10/2017	0.029 ± 0.083	0.106 ± 0.131	0.783 ± 0.194	0.075 ± 0.102	0.008 ± 0.036
Male	9/10/2017	0.025 ± 0.075	0.08 ± 0.098	0.832 ± 0.155	0.053 ± 0.07	0.01 ± 0.049
Male	11/10/2017	0.027 ± 0.08	0.088 ± 0.107	0.819 ± 0.164	0.056 ± 0.074	0.01 ± 0.045
Male	16/10/2017	0.027 ± 0.078	0.086 ± 0.104	0.825 ± 0.16	0.051 ± 0.067	0.011 ± 0.051
Male	24/10/2017	0.024 ± 0.071	0.077 ± 0.094	0.834 ± 0.154	0.054 ± 0.075	0.011 ± 0.052
Male	24/10/2017	0.024 ± 0.069	0.078 ± 0.093	0.838 ± 0.156	0.046 ± 0.064	0.014 ± 0.064
Female	8/11/2017	0.028 ± 0.086	0.104 ± 0.134	0.806 ± 0.185	0.052 ± 0.073	0.01 ± 0.046
Male	8/11/2017	0.022 ± 0.066	0.072 ± 0.087	0.847 ± 0.152	0.044 ± 0.061	0.015 ± 0.068
Male	13/11/2017	0.029 ± 0.084	0.106 ± 0.132	0.787 ± 0.19	0.069 ± 0.097	0.008 ± 0.037
Female	13/11/2017	0.03 ± 0.092	0.139 ± 0.186	0.728 ± 0.249	0.097 ± 0.14	0.007 ± 0.031
Female	24/11/2017	0.027 ± 0.083	0.094 ± 0.123	0.819 ± 0.176	0.049 ± 0.071	0.011 ± 0.049

a degree of correlation ($R^2 = -0.59$) which may affect the ability of our models to accurately differentiate between these prey sources (Inger et al. 2010). Mixing models showed that on average, no more than 3% of stoat diet was comprised of mallard tissue (Table 3, supplementary material (Figure S1)).

Discussion

This study has demonstrated that bird eggs are a readily consumed food item for stoats in the Southland agricultural environment. Remnants of bird eggs were found in one third of stoat stomachs and the isotope mixing models suggest that on average, bird eggs made up between approximately 73–85% of the individual metabolic requirements of stoats during the mallard breeding period. Stomach analysis revealed only two stoat stomachs contained mallard prey; one had consumed mallard egg and one had consumed mallard duckling tissue and feathers. However, isotope mixing model outputs revealed that bird eggs could make up a significant proportion (approximately 77–84%) of assimilated stoat diet early in the mallard breeding period (mid-August – early-September) when mallard egg availability is high and alternative bird egg (passerine) availability is low. In contrast, mixing model outputs suggested mallard ducks/ducklings made up a minor proportion of assimilated stoat diet.

The prevalence of bird eggs in the diet of the captured stoats was expected as eggs have been identified as a common stoat prey item (King 2005) and, when readily available, can make up a substantial proportion of stoat diet (Murphy et al. 2004; Dowding et al. 2015). The isotope mixing models could not differentiate between stoat consumption of mallard eggs and passerine eggs because the isotopic signatures of these two prey types did not differ sufficiently in isospace and therefore they had to be grouped as the prey category 'bird eggs'. However, five stoats were captured early in the mallard nesting period (mid-August – early-September) (Sheppard 2017), before our first record of small bird egg consumption by a stoat (11 September) and well before the peak nesting period of blackbirds, song thrushes and European starlings (late September – October) in New Zealand (Gurr 1954; Flux 1966; Flux and Flux 1981; Bull and Flux 2006). As such, mallard eggs were the main egg type available during this time and were potentially consumed by these stoats as suggested by the isotope mixing models. The high bird egg dietary proportion estimates in these five stoats suggests that mallard eggs may be readily consumed by stoats and mallard nests may be vulnerable to stoat predation early in the breeding period when there are fewer alternative prey items (i.e. small bird eggs) available.

If stoats are consuming mallard eggs early in the breeding season, this is of concern for gamebird managers. Sheppard (2017) found that mallard hens which initiate nests earlier in the breeding season are the experienced hens, which are more successful at raising ducklings relative to inexperienced hens. If stoats are preying upon mallard eggs during the early part of the peak nest period, as the stable isotope mixing models may suggest, stoats could be disturbing nests and removing eggs from the most successful mallard brood raisers and consequently stoat disturbance of early nests may have a disproportionately large effect on the mallard population.

Both the stomach content analysis and isotope mixing models indicate limited stoat consumption of mallard ducks or ducklings in the period of this study. The average contribution of mallards to stoat dietary estimates did not exceed 3% in mixing model outputs.

This was surprising because in Sheppard's (2017) mallard hen radio tracking study, 16% of hens fitted with abdominal transmitters at the Southland study site were killed during the main nesting/brood rearing period (Southland Fish and Game, unpublished data). Furthermore, duckling survival was low, ranging from 16–30% depending on maternal experience. Theoretically, there should be many opportunities for stoats to prey upon or scavenge mallard hens or ducklings. There are several potential explanations for the limited evidence of mallard consumption by stoats. Firstly, it may be that there was an abundance of energetically less demanding prey items (i.e. eggs) available to stoats and they prefer to target these prey items; stoats have been known to preferentially select more energetically rewarding prey types as they become available (Smith et al. 2011). Secondly, stoats can exhibit surplus killing behaviour (Oksanen et al. 1985) and may be killing mallard hens and ducklings but not consuming them during the period represented by this study. Finally, it may be that an alternative predator, potentially feral cats, were responsible for the mallard hen and duckling predation outlined in Sheppard (2017). Notably, feral cats are abundant in the immediate study area (minimum density estimate of 2.88 individually identifiable free-range cats per km^2) (Southland Fish and Game, unpublished data) and cats are known to be duckling predators (Morgan 2002).

Mallard population models have revealed that mallard duckling and hen survival are the two most important variables influencing the New Zealand mallard population whilst nest survival is a second-tier variable (Sheppard 2017). As such, any mallard egg predation by stoats may negatively affect the mallard population to some extent, but this research indicates stoats are unlikely to be the most important mallard predator. Future research should assess the importance of mallard hens and ducklings in the diet of feral cats to determine whether mallards feature prominently in their diet.

There are two caveats associated with the stable isotope component of this work. Firstly, species specific lipid normalisation equations were not available to correct for lipid content in the prey muscle tissues. However, general mammal/bird lipid normalisation equations were used and provide an accurate and convenient way to account for lipids (Ehrich et al. 2011) whilst preserving $\delta^{15}N$ integrity (Post et al. 2007). Secondly, species-specific (stoat) TEFs were not used when accounting for trophic fractionation in the isotope mixing models. This has incorporated an unknown amount of error into the mixing model outputs (Bond and Diamond 2011) and therefore dietary proportion estimates should be viewed as a first approximation. Despite this, the proxy TEFs utilised were of an obligate carnivore with a fast metabolic rate (McNab 1989), all consumer values fell within the prey isospace, and the results make biological sense. For example, when lagomorphs are abundant in a landscape they feature heavily in the diet of stoats (King and Moody 1982; Alterio and Moller 1997; Dowding and Elliott 2003). In the study area, lagomorph abundance is low (pers. obs., pers. comm. D Burgess, Environment Southland). Correspondingly, the mixing model results have shown lagomorphs to be unimportant prey items for Southland stoats during the mallard nesting and brood rearing period. These factors combined suggest that the TEFs utilised were suitable surrogates in the lack of stoat-specific factors and the study yields biologically reasonable results (Fry 2006; Smith et al. 2013; Stock et al. 2018).

This study has provided the first detailed insight into stoat foraging ecology in the Southland agricultural environment. While past research has focussed on stoats as predators of native species in relatively intact ecosystems, the goal of totally removing stoats

from New Zealand (Department of Conservation 2016) has led to a large increase in predator trapping in non-native human modified habitat (Department of Conservation 2018a, 2018b; Glen et al. 2019). This study provides valuable contribution to our knowledge of stoat diets in an agricultural landscape and will help inform communities of likely effects of stoat control in these areas. While stoats were identified as a predator of bird eggs in these settings, results from this study indicate stoats are not heavily consuming mallard hens or ducklings. If confirmed, this would indicate that single species pest control may not achieve a desired outcome for fauna of interest. This has strong relevance to managers when deciding which predator guilds should be targeted for the benefit of species of interest.

In conclusion, this study indicates that stoats are an egg predator in the Southland agricultural landscape and mallard eggs may comprise a substantial proportion of assimilated diet early in the mallard breeding season. There was limited evidence that stoats consumed mallard ducks or ducklings which suggests that other predators, potentially cats, are more likely to be prolific mallard predators. Future research should use motion-activated cameras to confirm stoat predation of mallard nests, particularly early in the mallard breeding period and, quantify the prevalence of mallards in the diet of feral cats.

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Appendix 1

Mean $\delta^{15}N$, $\delta^{13}C$ and $\delta^{13}C$ lipid corrected value of potential stoat prey items from Lochiel, Southland, New Zealand. Values presented as means ± one SEM with range in brackets. Values for mallard eggs and small bird eggs are from lipid extracted homogenised yolk and albumen.

Prey item	$\delta^{15}N$	$\delta^{13}C$	$\delta^{13}C^{Lipid\ normalised}$
Mallard hen ($n = 8$)	8.7 ± 0.2	−27.6 ± 0.3	−26.8 ± 0.3
	(7.7, 9.6)	(−29.2, −26.7)	(−28.2, −25.9)
Mallard duckling ($n = 5$)	8.8 ± 0.4	−27.5 ± 0.3	−26.5 ± 0.3
	(7.7, 9.6)	(−28.1, −26.7)	(−27.1, −25.7)
Mallard (mallard hen and duckling combined) ($n = 13$)	8.7 ± 0.2	−27.6 ± 0.2	−26.7 ± 0.2
	(7.7, 9.6)	(−29.2, −26.7)	(−28.2, −25.7)
Small bird ($n = 7$)	9.00 ± 0.3	−26.4 ± 0.3	−25.5 ± 0.3
	(8.00, 9.9)	(−27.6, −24.6)	(−26.3, −23.8)
Small bird egg ($n = 5$)	8.8 ± 0.4	−27.1 ± 0.1	
	(7.9, 9.9)	(−27.3, −26.9)	
Mallard egg ($n = 5$)	8.5 ± 0.2	−27.4 ± 0.2	
	(7.9, 9.2)	(−28.0, −26.9)	
Egg (mallard egg and small bird egg combined) ($n = 10$)	8.6 ± 0.2	−27.3 ± 0.1	
	(7.9, 10.0)	(−28.00, −26.9)	
Rat ($n = 4$)	11.4 ± 1.2	−27.5 ± 0.5	−25.1 ± 0.3
	(9.00, 14.6)	(−28.4, −26.00)	(−25.6, −24.8)
Mouse ($n = 3$)	12.00 ± 1.6	−27.0 ± 0.1	−25.1 ± 0.3
	(8.9, 14.4)	(−27.3, −26.8)	(−25.7, −24.8)
Rodent (rat and mouse combined) ($n = 7$)	11.7 ± 0.9	−27.3 ± 0.3	−26.0 ± 0.5
	(8.9, 14.6)	(−28.4, −26.0)	(−27.6, −24.8)
Hare ($n = 3$)	5.9 ± 1.1	−30.0 ± 0.3	−28.9 ± 0.3
	(4.6, 7.9)	(−30.4, −29.3)	(−29.7, −28.9)
Rabbit ($n = 2$)	5.2 ± 0.04	−29.0 ± 0.01	−28.3 ± 0.002
	(5.1, 5.2)	(−29.0, 29.0)	(−28.3, −28.3)
Lagomorph (hare and rabbit combined)	5.6 ± 0.6	−29.6 ± 0.3(−30.4, −29.0)	−28.7 ± 0.2
	(4.3, 7.9)		(−29.4, −28.3)