Eradication of stoats (Mustela erminea) from Secretary Island, New Zealand

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Abstract Stoats (Mustela erminea) are known to be good swimmers. Following their liberation into New Zealand, stoats reached many of the remote coastal islands of Fiordland after six years. Stoats probably reached Secretary Island (8140 ha; 1196 m), at the entrance to Doubtful Sound on the western coastline of Fiordland National Park (Fig. 1), the second largest island on the Fiordland coast and the third highest island in New Zealand. The island is separated from the mainland portion of Fiordland by Thompson Sound to the east (minimum distance between the two is C. 950 m), and by Doubtful Sound to the south (minimum distance to closest post population is two passages C. 170 m and 600 m via Bauza Island which is largely stoat-free).

INTRODUCTION

Stoats (Mustela erminea) were first introduced into mainland New Zealand in the late 1880s in response to feral rabbit (Oryctolagus cuniculus) plagues that were destroying pasturelands and posing a serious threat to the New Zealand economy. Stoats have had dramatic effects on New Zealand’s naïve native animal species, many of which evolved without terrestrial predators (King 1984). Stoats are very mobile and are capable swimmers (Taylor and Tilley 1984) and were observed by Richard Henry, curator on Resolution Island in Fiordland, by 1900 (Hill and Tilley 1984) and were exhibited by Richard Henry, curator on Resolution Island in Fiordland, by 1900 (Hill and Hill 1987). The stoats probably invaded other remote islands in Fiordland, including Secretary Island, at around the same time.

Secretary Island is administered by the New Zealand Department of Conservation. In 2004, it became the focus of a 10-year programme to eradicate stoats and red deer (Cervus elaphus) (Edge et al. 2011). Techniques for eradicating stoats from islands had been piloted successfully on several smaller islands in Fiordland (Elliott et al. 2010). Stoats had also been trapped on 19 islands ranging in size from 1 - 67 ha and within varying distances from the mainland over a four-year period, in order to produce a predictive model of stoat reinvansion; of 46 stoats captured, only one was caught on an island further than 304 m offshore. Based on these results, Elliott et al. (2010) concluded that large islands like Secretary and Resolution would be suitable for stoat eradication attempts. Our paper describes an approach to the eradication of stoats from Secretary Island based on an operational plan with two key objectives (Golding et al. 2005):

1. To eradicate stoats from Secretary Island. The plan defined ‘eradication’ as the complete removal of the resident stoat population and the establishment of a long-term control and monitoring programme to manage reinvasion.

2. To achieve and maintain a zero-density stoat population on Secretary Island so that indigenous species currently existing on the island or introduced to the island can thrive.

METHODS

Study area

Secretary Island (8140 ha; 1196 m), at the entrance to Doubtful Sound on the western coastline of Fiordland National Park (Fig. 1), is the second largest island on the Fiordland coast and the third highest island in New Zealand. The island is separated from the mainland portion of Fiordland by Thompson Sound to the east (minimum distance between the two is C. 950 m), and by Doubtful Sound to the south (minimum distance to closest post population is two passages C. 170 m and 600 m via Bauza Island which is largely stoat-free).

In 1963, Secretary Island was designated a ‘Special Area’ within Fiordland National Park by the New Zealand Government due to the island’s unmodified vegetation and the real (or apparent) absence of introduced browsing or grazing animals including the brushtail possum (Trichosurus vulpecula) and red deer. Introduced rodents were also absent, making Secretary Island the largest inshore island in New Zealand free of such pests. Stoats were the only mammalian pests known to be present. Red deer probably arrived in the late 1950s (Mark and Baylis 1975), but it took some time for a population to establish (Crouchley et al. 2011).
Stoat trapping on Secretary Island

Full details of methods for the trapping programme on Secretary Island are provided in the Operational Plan (Golding et al. 2005). In brief, these involved the following techniques.

A 108 km network of trap lines was established on Secretary Island from October 2004 to April 2005 along main ridge lines and spurs, habitat boundaries, waterways and traversable terrain (Fig. 2). Based on previous successful eradications of stoats from islands in Fiordland, we needed a minimum average density of one trap tunnel per 9 ha (Elliott et al. 2010.). We also needed to ensure that every stoat on the island would encounter a trap (Parkes 1990; Parkes et al. 2002). Home range estimates for stoats vary according to gender, season, and food availability, so it was important to determine the smallest likely home range in order to decide the maximum spacing between traps. Home ranges are smallest when prey, especially rodents, is easily available. For example, average home ranges were 93 (SE±7) ha for four male stoats and 69 (SE±8) ha for five female stoats in a Fiordland beech (Nothofagus sp.) forest when rodents were abundant (Murphy and Dowding 1995). Larger stoat home ranges were reported in areas where rodents are scarce, with estimates of 204 ha for males and 124 ha for females (Murphy and Dowding 1995), 223 ha for males and 94 ha females (Alterio 1998), and 210 ha for males and 89 ha females (Miller et al. 2001). Without similar home range information for stoats on Secretary Island, our trap network was based on the smaller home range sizes of Murphy and Dowding (1995), which meant that wherever possible traps should be no more than 700 m apart. However, due to the extremely rugged terrain on the island there were seven locations where this distance exceeded 700 m (see Fig. 2).

A total of 945 tunnels each containing 2 Mark IV Fenn kill traps (DB Springs Ltd. Worcestershire, England) were placed at 135 m intervals along the trap lines and at 150 m intervals along the eastern coastline (accessible by boat), yielding an average tunnel density of 1 tunnel per 8.6 ha (Fig. 2).

Two tunnel types were used to house traps: 300 wire mesh tunnels with wooden bases and 645 wooden tunnels with wire mesh ends. Wooden and wire mesh tunnels were placed in a repeated sequence along trap lines comprising one wire tunnel followed by two of wood. The variation in tunnel types was used to overcome any possibility that a few stoats were unwilling to enter either one type of tunnel.

Previous stoat eradications in Fiordland used pre-baiting whereby stoats were free to enter traps set with the safety catch on and with bait was left inside and outside the trap entrance. It is not possible to determine how crucial pre-baiting has been to the success of these programmes. Pre-baiting is relatively inexpensive and the amount of bait-take observed during the pre-baiting phase suggests it may reduce the time taken to achieve the initial knock-down. Traps were pre-baited twice on Secretary Island: 20 June - 26 June and 5 July - 11 July 2005. During pre-baiting, each tunnel site was baited with one fresh hen’s egg and a piece of meat (ca 3 cm cube of beef, rabbit or venison) on the bait block between traps. An additional hen’s egg was also placed outside the trap tunnel on the ground and another approximately 1 m off the ground on a tree.

Stoat trapping began on Secretary Island from 20 - 30 July 2005 using the pre-baiting regime. Traps were
checked twice during this initial trapping period and were only re-set or re-baited if required. Thereafter traps were left set and baited, then serviced three times annually in November, February and between May and July.

The location, tunnel type, type of bait used, weight and sex of each stoat trapped were recorded and the carcass frozen for future analyses of diet and aging using cementum analysis of teeth. Sex was determined from the presence/absence of a baculum bone, unless the specimen was badly degraded, in which case it was recorded as “unknown”. Tissue or bone samples were taken from all stoats captured for DNA analysis.

In July 2006, all wire mesh tunnels were removed from the island due to disturbance from native birds such as kaka (Nestor meridionalis), kea (N. notabilis), and weka (Gallirallus a. australis). Concurrently, each wooden tunnel was modified to contain a single trap. In July 2007, all remaining traps were replaced with single-set stainless steel DOC 150 traps (CMI Springs Ltd. Wellington, NZ).

Managing reinvasion

A coastal trap line comprising 180 double-set DOC 150 traps in wooden tunnels was established on the mainland along Thompson Sound and Pendulo Reach (Fig. 2). Stepping-stone islands to the south and south-east were already being trapped as part of the Fiordland Stoat Immigration Study (Elliott et al. 2010). Trapping on the mainland (hereafter referred to as Mainland) commenced in March 2005 with a subsequent check during the initial knockdown on Secretary Island. Thereafter, traps were serviced in November and February, which activated traps with fresh bait immediately before juveniles left their natal den, and cleared the traps after most juveniles had dispersed to establish new territories (King and Powell 2007).

Monitoring for stoats at low density

Tracking tunnels were not used to monitor stoat activity on the island because their rigorous use required a very large number to be set and serviced (Brown and Miller 1998; Choquenot et al. 2001; King et al. 2007). Given that the probability of a stoat entering a tracking tunnel and a kill-trap tunnel is similar, we viewed dead stoats in traps as preferable to stoat footprints in tracking tunnels. Based on the success of previous stoat eradication operations in Fiordland up to 2004, we assumed that kill-traps would provide good detectability for stoats at low density. Trained stoat-indicator dogs were used on and off the tracks and we also requested contract deer hunters to record their observations of stoat sign.

Molecular data

Molecular DNA techniques have successfully identified survivors from invaders following island rat eradication programmes (Adhelkrim et al. 2007; Rollins et al. 2006; Russell et al. 2010). To be useful, the technique requires measurable genetic differentiation between sample populations. We used molecular analysis to determine the frequency of immigration by stoats to Secretary Island following the initial knockdown.

DNA extraction and microsatellite amplification

Of 189 stoats caught, 89 were used in the genetic analysis. Fifty-four stoats were from Secretary Island, including 10 from July 2005, 25 from February 2006, 5 from February 2007, 6 from May 2007, 1 from June 2007, 1 from January 2008, and 7 from June 2008. Thirty-four samples were obtained from stoats trapped on the adjacent Mainland from July 2005 - January 2008. Sub-sampling from July 2005 and February 2006 was random, thereafter all of the stoats captured were analysed for each of the stated time periods. The intention is to include all of the stoats caught for all time periods for future analysis.

Tail tissue samples were dissected in the laboratory, where 50 mg of muscle tissue and caudal skin were removed. DNA was then isolated, using a Bio-Rad AquaPure Genomic Tissue Kit (Cat# 732-6345) following the manufacturer’s protocol, and re-suspended in 100 μl of supplied buffer.

All samples were genotyped using sixteen microsatellite loci developed from a range of mustelid species. Primers used were MER005, MER030, MER022, MER041, MER009, and MER082 developed from M. erminea (Fleming et al. 1999); MV1057 developed from M. vison (O’Connell et al. 1996); WE7 and WE8 from M. sibirica (Huang et al. 2007); MLUT27 and MLUT32 developed from M. lutropola (Cabria et al. 2007); MA1 developed from Martes americana (Davis and Strobeck 1998); MEL1 and MEL4 developed from Meles meles (Bijlsma et al. 2000); RIO11 and RIO19 developed from Lantra canadenis (Beheler et al. 2005). PCR amplification and genotyping followed Gleeson et al. (2010).

DNA analysis

For statistical purposes, the data were grouped into three ‘populations’: 1) Secretary Island residents (n=35) consisting of 10 from the initial knockdown and 25 trapped in February 2006 (these latter were mostly juveniles and considered to be survivors from the initial knockdown); 2) all stoats trapped from February 2007 – June 2008 (n=20); and 3) all samples from the nearby mainland site (n=35) from July 2005 - January 2008.

Microsatellite genotypes were analysed using GenALEx v. 6.2 (Peakall and Smouse 2006) to generate observed and expected heterozygosities, allele frequency scores and Hardy-Weinberg equilibriums. Pairwise Fst parameters for each population pair were estimated according to Weir and Cockerham (1984). The data were analysed using the Bayesian clustering method implemented in STRUCTURE ver 2.3 (Pritchard et al. 2000) to provide another estimate of pairwise Fst parameters and to determine the number of distinct genetic units (K) in the dataset. This method does not require prior knowledge of sampling localities and assigns individuals into groups minimising deviations from Hardy-Weinberg proportions and genotypic linkage equilibrium. The admixture model with correlated allele frequencies was chosen. Ten replicates were conducted for each run, consisting of a burn-in period of 100,000 MCMC (Markov Chain Monte Carlo) steps followed by 106 iterations. The ΔK method of Evanno et al. (2005) was applied and plots of the log posterior probability of the data [lnP(D)] for each value of K examined.

Assignment tests were carried out to determine the most probable origin of the individuals captured after the initial eradication operation using GENECLASS 2.0 (Piry et al. 2004). The likelihood of the multilocus genotype of each individual being assigned to the resident Secretary Island population or the Mainland population was calculated in order to identify putative residual individuals or migrants. Ten thousand MCMC simulations per population were run using the Lh/Lmax likelihood computation (Paetkau et al. 2004). An individual was considered to be a disperser if the Lh/Lmax P value was below 0.01.
**RESULTS**

**Secretary Island stoat captures**

**Prebaiting and Trapping**

Bait was taken from 95% and 99% of all trap tunnels during the first and second pre-baiting periods respectively. Following the knockdown in July 2005 <10 stoats have been caught in each trapping period (Fig. 3) mostly in autumn and early winter. The sex ratio of captures was approximately 2 females for every male (Table 1). Stoat captures were generally well spread across the island with highest numbers in the west and north.

**Molecular analysis**

No significant linkage disequilibrium was detected between loci, so all loci included in the analysis were considered independent. The mean number of alleles per population (Table 2) ranged from 4.06 for the original Secretary Island population, 4.69 for the post-eradication Secretary Island population, through to 5.06 for the nearby Mainland population. There were no alleles of frequency > 0.05 restricted only in the original Secretary Island population, while there were five alleles found only in the post-eradication Secretary Island population, and two alleles restricted to the Mainland population. Ten alleles shared between post-eradication Secretary Island and the Mainland that were not found in the original Secretary Island population.

**FST** values between populations were relatively low, indicating little population structuring. Pairwise estimates were lowest between the post-eradication population and the mainland (0.006), and highest between the original Secretary Island population and the mainland (0.03). The STRUCTURE analysis showed only slight differences between average loglikelihood estimates across different population scenarios ranging from K=1 to K=5. The best scenario revealed from plotting these estimates was K=2. The proportion of membership (q) of each group to the two inferred clusters (Secretary Island vs Mainland) (Fig. 4) shows group 2 (post-eradication Secretary Island) individuals being an admixture of both sources.

GENECCLASS identified four individuals from the post-eradication Secretary Island population as first-generation immigrants from the mainland, while three individuals were assigned to the original Secretary Island population (Lh/Lmax P < 0.01).

**DISCUSSION**

Unlike previous eradications on smaller islands in Fiordland, not all stoats were removed from Secretary Island within the first year of trapping. Our results indicate that the stoat population is now being maintained at a very low number and, as a result of immigration and breeding by

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**Table 1** Sex of stoats caught on Secretary Island between July 2005 and December 2009.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Male</th>
<th>Female</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2005</td>
<td>34</td>
<td>56</td>
<td>5</td>
</tr>
<tr>
<td>Nov 2005</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Feb 2006</td>
<td>13</td>
<td>28</td>
<td>3</td>
</tr>
<tr>
<td>July 2006</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Nov 2006</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Feb 2007</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>May 2007</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Nov 2007</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Feb 2008</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>June 2008</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Dec 2008</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Feb 2009</td>
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<td>1</td>
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</tr>
<tr>
<td>May 2009</td>
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<td>1</td>
</tr>
<tr>
<td>Dec 2009</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2** Summary statistics for stoats from Secretary Island and Mainland. N = Sample Size; \( N_A \) = mean number of alleles per locus; \( N_{PA} \) = number of private alleles with frequency > 0.05; \( H_0 \) = observed heterozygosity; \( H_e \) = expected heterozygosity.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>N</th>
<th>( N_A )</th>
<th>( N_{PA} )</th>
<th>( H_0 )</th>
<th>( H_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secretary I.</td>
<td>2005-06</td>
<td>35</td>
<td>4.06</td>
<td>0</td>
<td>0.498</td>
<td>0.539</td>
</tr>
<tr>
<td>Secretary I. post eradication</td>
<td>2007-08</td>
<td>20</td>
<td>4.69</td>
<td>5</td>
<td>0.491</td>
<td>0.579</td>
</tr>
<tr>
<td>Mainland</td>
<td>2005-08</td>
<td>34</td>
<td>5.06</td>
<td>2</td>
<td>0.471</td>
<td>0.572</td>
</tr>
</tbody>
</table>

**Fig. 3** Stoot captures on Secretary Island from July 2005 to December 2009. Solid bars denote the period from which trapped animals were analysed using molecular DNA techniques. Arrows indicate stoot plague events on the adjacent mainland driven by beech (*Nothofagus* sp.) masting events in the preceding autumn causing an increase in rodent numbers.

**Fig. 4** STRUCTURE bar plot of estimation of the membership coefficient (Q) for each individual stoot for the three groups for K = 2. Each individual is represented by a thin vertical line, showing degree of admixture. Black lines separate individuals from each of different population groups based that are labelled below the figure.
residual resident animals, there has been no further decline. This latter finding may be related to the island’s size. Many eradication programmes against mobile carnivorous predators have taken several years to reach completion. Examples include cats (Felis catus) (Bester et al. 2000; Veitch 2001; Algar et al. 2002), stoats (Crouchley 1994), and mink (Neovision vison) (MacDonald and Harrington 2003).

Recent home range estimates obtained for stoats on Resolution Island (home range diameter C. 486 m; Clayton et al. 2011) indicate that the decision to space trap lines at a distance no greater than 1400 m apart may have been an over-estimate of resident stoat home range. On Secretary Island, a few stoats may have retained very small home ranges, despite the significant population reduction, and have therefore failed to encounter a trap. Since female stoats have smaller home ranges than males they may be less likely to encounter a trap. Nonetheless, twice as many females as males were trapped. Alternatively, some stoats may avoid entering a trap tunnel either for extended periods of time, or even in perpetuity, as was the case on Maud Island, New Zealand (Crouchley 1994). On Secretary Island, stoat tracks were twice recorded in snow along ridgelines with traps present, which indicated trap avoidance. Based on Maud Island experiences, continued trapping can eventually eliminate stoats that have avoided traps for periods of up to several years.

Genetic data revealed enough variability across all loci to show some degree of differentiation between the mainland and original Secretary Island population, although $F_{ST}$ values were relatively low. Differentiation between these groupings was supported by the STRUCTURE analysis which showed the data to be effectively split into two groupings. Evidence for immigration amongst the remaining stoats captured on Secretary Island after the initial year was from allelic differences (new alleles appearing) and from the assignment test using GENCLASS, which identified four first generation immigrants. There were also three individuals from that group which were assigned to the residential island population, while the remainder were unable to be assigned to either group, so were most likely admixtures from both.

The level of immigration detected from July 2005 to June 2008 was higher than predicted by Elliott et al. (2010) possibly due to beech masting in 2006 and a subsequent rodent and stoat plague on the mainland in Fiordland. During mast years, it is likely that there will be higher numbers of juvenile stoats dispersing from the mainland to inshore islands, such as Secretary Island. In February 2007, one stoat was caught on Seymour Island to the south of Secretary Island, the first in seven years of trapping. Another stoat was seen on Anchor Island, which had been free of stoats since 2001.

Further genetic work to include all of the stoats captured on the island since 2005 should help to refine the estimate for immigration. Molecular tools will also be used to determine the relatedness among individuals, thereby providing an estimate of population productivity; the absence of rodents on Secretary Island may mean that female litter size is reduced, which would explain why the number of stoats caught in summer on Secretary Island is not higher. King et al. (2003) demonstrated the significance of rodents driving population productivity in four beech forest sites in Fiordland. A shortage of rodents can lead to increased mortality of embryos and young in the den, while adult females remain healthy.

Low population productivity on Secretary Island strengthens the chances of eradication, which thus remains a key objective. A harsher winter, further refinements with the existing trapping programme or new technologies may hasten removal of the residual population. Moreover, stoat numbers have remained sufficiently low on Secretary Island to achieve anticipated conservation outcomes such as the reintroduction of several species of threatened birds (Wickes and Edge 2009). Monitoring species particularly vulnerable to stoats will be crucial in order to establish a stoat density threshold for future reintroductions, such as tieke/ South Island saddleback (Philesturnus C. carunculatus) proposed for 2015. The challenge is to detect stoats at extremely low densities without establishing a prohibitively expensive monitoring programme.

GENERAL CONCLUSIONS

Our programme was based on applying techniques developed on smaller islands over a much larger area. Although we planned to put all animals at risk of capture, this appears not to have been achieved, probably due to a broader range of habitat types than anticipated in the Secretary Island landscape. We also assumed that the level of reinvasion would be lower than preliminary genetic results have indicated. The experimental nature of this programme has opened the door for testing new ground in the field of island eradications and challenging some of the previously held views of what should and should not be attempted (see Edge et al. 2011). Molecular DNA tools have been invaluable in enabling managers to better understand what has happened on the island since the campaign began.

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Island invasives: eradication and management


