Environmental predictors of stoat (*Mustela erminea*) and ship rat (*Rattus rattus*) capture success

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ABSTRACT

The association between capture success of stoats (*Mustela erminea*) and ship rats (*Rattus rattus*) and landscape-scale environmental predictors was explored using trapping data from three stoat control areas located in podocarp/broadleaved forest in New Zealand. Stoat capture success was higher at trap sites where a rat was also captured at the same trap or a stoat was captured at a neighbouring trap. Drier trap sites with good soil drainage and increased proximity to the operational trapping boundary were also associated with increased stoat capture. Rat capture success was higher at trap sites where a rat had been captured at a neighbouring trap, and at trap sites that were on steeper ground, more easterly facing and within forest habitat. Trap sites with generally poor soil conditions, i.e. sites with lower soil calcium levels and wetter sites with poor drainage, and increasing distance from the forest edge were also associated with increased rat capture. There were highly variable relationships between rat and stoat capture and landscape-scale environmental predictors between the three stoat control areas. This could be due to differing topography, but also to the highly correlated nature of many of the topographic, climate and habitat predictors. Further research specifically designed to separate these effects should focus on the variables identified as common between all stoat control areas in this study. Additional investigations of whether rats captured in double trap sets act as additional bait for stoats would have practical benefits for stoat control areas. The variability of the results emphasises the importance of ensuring that traps are abundant and widespread in stoat control operations.

Keywords: *Mustela erminea*, stoats, *Rattus rattus*, ship rats, predator control, logistic regression, GIS, mustelid, Fenn trapping, New Zealand

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1. Introduction

Stoats (*Mustela erminea*) were introduced to New Zealand in the late 1800s to control rabbits (*Oryctolagus cuniculus*). They spread rapidly and have since become a significant predator of New Zealand's native fauna (O'Donnell 1996; King & Murphy 2005). Ship rats (*Rattus rattus*) were accidentally introduced with the arrival of Europeans in New Zealand and were well established by the late 19th century (Innes 2005). Studies have shown that the control of stoats and rats results in increased survival and productivity for some native species (Elliot 1996; McLennan et al. 1996; Gillies et al. 2003; Moorhouse et al. 2003). The level of predator control necessary is dependent on the damage threshold for the target native species to be protected.

Since the mid-1990s, native species protection programmes in New Zealand have increasingly used large-scale landscape trapping to control stoats, with rats (mostly ship rats) a common by-catch species. Kiwi (*Apteryx* spp.), kaka (*Nestor meridionalis*), mohua (*Mohoua ochrocephala*) and takahe (*Porphyrio mantelli*) are just some of the native species protected with varying success using this method. Success has been variable, because there will always be an unknown number of stoats or rats that remain untrapped. To increase success, the trappable component of the stoat or rat population needs to be increased. This could potentially be achieved in two ways: by increasing effort (i.e. increasing trap intensity, covering a larger area with traps, or checking more frequently) or by targeting effort more efficiently and thus improving capture success at individual traps. Patterns of stoat and rat captures are often patchily distributed across a control operation, with some traps consistently catching stoats, and neighbouring traps of successful traps frequently also catching stoats. Therefore, if these patches can be related to environmental predictors using exploratory modelling, the efficacy of trapping operations could be improved by increasing control effort in patches with similar characteristics.

Recent investigations, both in New Zealand and elsewhere, have demonstrated the usefulness of analysing trapping data using an exploratory modelling approach to predict the occurrence of small mammals according to habitat type (e.g. Cox et al. 2000; Kolowski & Woolf 2002; Wheatley et al. 2005). These studies include investigation of the influence of microsite characteristics at trap-sets on stoat capture probability (Christie et al. 2006) and a number of investigations of ship rat habitat use patterns (e.g. Dowding & Murphy 1994; King et al. 1996; Blackwell et al. 1998; Cox et al. 2000; Studholme 2000). Large amounts of data are available from the large-scale stoat control operations carried out around New Zealand, and it is becoming increasingly attractive to use these data in exploratory modelling analyses. There is also increasing pressure from conservation managers and researchers to use this type of data to identify capture 'hotspots' and thus increase trapping efficacy.

This study uses data from three stoat control areas that were set up with the primary objective to protect kiwi. It builds on findings from a related study (Christie et al. 2006) that focussed on the relationship between small-scale (microsite) predictor variables (measured at the actual trap site) and capture success at two stoat control areas. This report expands on the Christie et al. (2006) study by:

- Using trapping data from three stoat control areas over a longer period
- Relating stoat and rat capture success to large-scale computer-generated spatial environmental predictor variables
- Generating spatial predictor surfaces (maps) of stoat and rat capture probability

It also aims to provide information and recommendations for predator control operation managers, with regard to data management and analysis limitations. Recommendations for practical improvements to future trapping operations are unlikely at this exploratory stage of the research process, because of model selection uncertainty and the low strength of inference associated with this type of exploratory modelling (Burnham & Anderson 2002). However, findings with practical implications are identified as future research priorities.

2. Objectives

This study had three objectives:

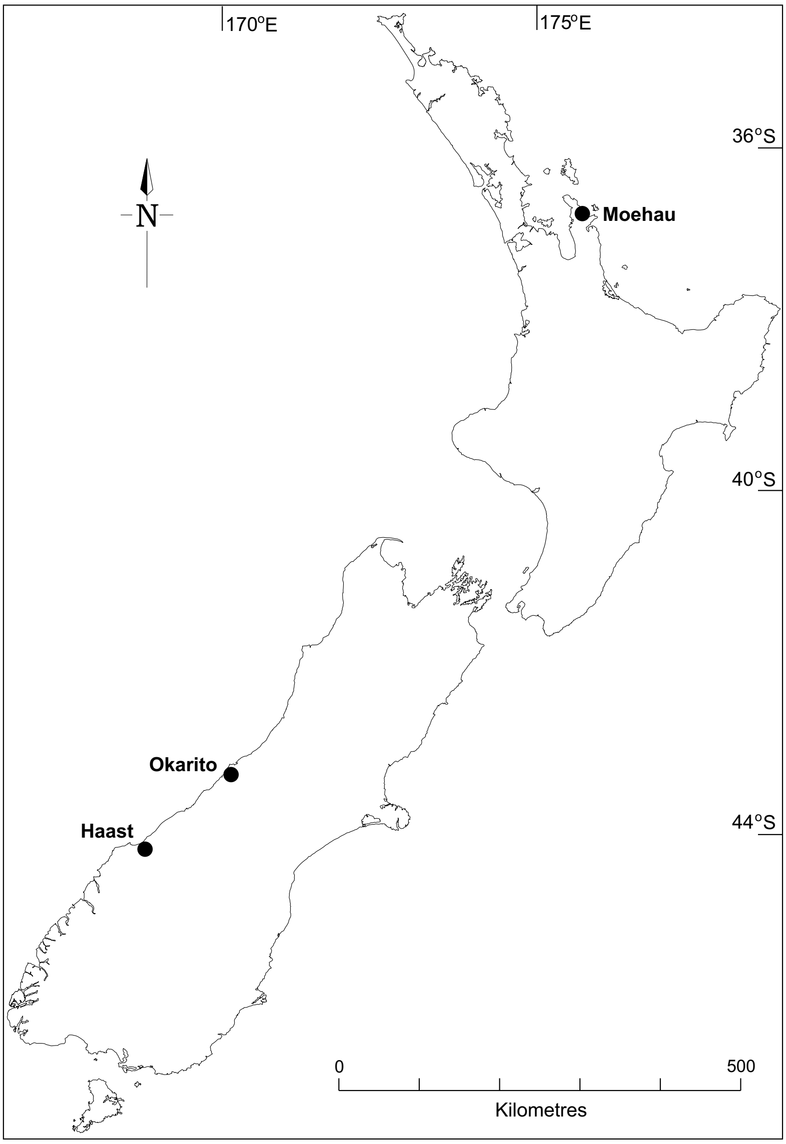
1. To identify large-scale environmental variables that are predictors of stoat and rat capture success; in particular, which environmental predictor variables are common to more than one stoat control area.
2. To investigate the effectiveness of using post-hoc exploratory modelling techniques to analyse trapping data from stoat control operations.
3. To make recommendations for future research priorities.

3. Methods

3.1 STUDY AREAS

Trapping data were collected from three large-scale stoat control areas set up as sanctuaries to protect kiwi. One of these stoat control areas is located at the tip of the Coromandel Peninsula, at Moehau (36°43′S, 175°31′E), and two are located in South Westland at Okarito (43°15′S, 170°11′E) and Haast (44°05′S, 168°47′E) (Fig. 1). All three stoat control areas are located within native forest ecosystems dominated by podocarp/broadleaved forest species, but with varying underlying landscape and climatic features. The Moehau stoat control area is a temperate coastal/alpine (20–860 m a.s.l.) forest ecosystem. In contrast, Okarito and Haast are both cold temperate coastal wetland ecosystems. Okarito only contains low ridges (0–520 m a.s.l.), whereas the Haast stoat control area extends above the timberline (20–1470 m a.s.l.) into alpine grassland (*Chionochloa* spp.) with beech forest (*Nothofagus* spp.) on the upper hill slopes.

Figure 1. Location of stoat (*Mustela erminea*) control areas included in this study.



3.2 TRAPPING OPERATIONS

At all three stoat control areas, wooden tunnels containing either one (i.e. single set) or two (i.e. double set) Mark IV Fenn kill traps were laid out on a semi-permanent basis at approximately 200-m intervals along linear landscape features such as streams and ridge lines. These tunnel sites are referred to as 'trap sites' in this paper. Stoats were the primary trapping target, with rats a secondary by-catch. Both the area and intensity of the trapping layout varied between the three control areas (Table 1). Traps were set continuously, baited with one unbroken hen's egg, and checked every 2 weeks from summer to autumn, and once per month over the winter and spring months. For each stoat control area, trapping datasets contained information about the Global Positioning System (GPS) way-point location of each trap and a record of whether a stoat or rat was caught each time a trap was checked. The longest time period over which trapping data were available was from Okarito (30 months), followed by Haast (18 months), and then Moehau (6 months) (Table 1). At all three control areas, the initial trap opening date was staggered and trapping began 3–4 months prior to the beginning of the trapping dataset used in this study.

3.3 CALCULATING SPATIAL ENVIRONMENTAL PREDICTOR VARIABLES

Spatial environmental predictor variables included in the models are outlined in Table 2. These were generated from environmental surfaces contained in Geographic Information Systems (GIS) using ArcView/ArcGis with Spatial Analyst extension (ESRI, Redlands, California, USA). Nearest neighbour distances to specific objects, such as permanent water courses and bush edge, were calculated for each trap site using 1:50 000 topographical vector data (Land Information New Zealand). A digital elevation model with a resolution of 25 m was used to generate altitude, aspect and slope. Vegetation type was defined to a resolution of 20 m using the Land Cover Database (LCDB1) (Ministry for the Environment). Soil and climate variables were derived from Land Environments of New Zealand (LENZ; Leathwick et al. 2003).

TABLE 1. TRAPPING EFFORT AT THE THREE STOAT (*Mustela erminea*) CONTROL AREAS MODELLED IN THIS STUDY.

CONTROL AREA	SIZE (ha)*	NUMBER OF TUNNELS		NO. OF TRAPS PER TUNNEL	DATA TIME RANGE
		TOTAL*	MEAN/100 ha		
Moehau	16 500	2200	13.3	1	Spring 2002 – Summer 2002/03
Okarito	10 000	1500	15.0	1–2	Spring 2001 – Autumn 2003
Haast	12 000	615	5.1	2	Winter 2001 – Summer 2002/03

* Approximate values.

TABLE 2. ENVIRONMENTAL VARIABLES USED AS PREDICTORS IN THE SEASONAL AND ANNUAL MODEL ANALYSES.

Note: Not all predictor variables were used in each model, as some were eliminated before modelling for various reasons (see text).

PREDICTOR VARIABLE	DEFINITION (DATA SOURCE)	TYPE OF VARIABLE	UNITS	CATEGORY
Annual temperature	Monthly mean daily temperature, averaged across all months (Land Environments New Zealand (LENZ))	Continuous	°C	Climate
Minimum temperature	Mean daily minimum temperature of the coldest month, usually July (LENZ)	Continuous	°C	Climate
Annual solar radiation	Monthly mean daily solar radiation averaged across all months (LENZ)	Continuous	$MJ/m^2/day$	Climate
Winter solar radiation	Mean daily solar radiation in June (LENZ)	Continuous	$MJ/m^2/day$	Climate
Rainfall to potential evaporation	Monthly estimates of rainfall / potential evaporation averaged across all months (LENZ)	Ordinal	Ratio	Climate
Vapour pressure deficit	The capacity of air to take up water vapour in spring (October), dependent on temperature and humidity (LENZ)	Ordinal	kPa	Climate
Phosphorus	Analysis of sub-soil phosphorus concentration using half-molar sulphuric acid (LENZ)	Ordinal	5-step scale	Substrate
Substrate age	Time elapsed since major reset of soil formation, separating young from old soils (LENZ)	Ordinal	2-step scale	Substrate
Calcium	Analysis of exchangeable soil calcium (LENZ)	Ordinal	4-step scale	Substrate
Hardness	Physical resistance of parent material to breakdown (LENZ)	Ordinal	5-step scale	Substrate
Particle size	Average size of parent material (LENZ)	Ordinal	5-step scale	Substrate
Drainage	The rate of water removal from the soil by runoff, percolation and evaporation (LENZ)	Ordinal	5-step scale	Substrate
Chemical limitations	Indicating where chemicals accumulate at high enough levels to limit plant growth (LENZ)	Ordinal	3-step scale	Substrate
Water deficit	The sum of monthly amounts by which evaporation exceeds rainfall for a whole year (LENZ)	Continuous	mm	Climate
Slope	Slope estimated from digital elevation model	Continuous	Degrees	Landform
Altitude	Altitude above sea level estimated from digital elevation model	Continuous	m	Landform
Easterly aspect	Sine of aspect estimated from digital elevation model	Continuous	Radians	Landform
Northerly aspect	Cosine of aspect estimated from digital elevation model	Continuous	Radians	Landform
Forest	Presence of indigenous mature forest, derived from Land Cover Database 1 (LCDB1)	Binary	0/1	Land cover
Stoat 500 m	Ratio of stoats captured in 500-m radius of trap to the number of traps in a 500-m radius within the same time frame	Continuous	Ratio	Trap competition/ patch size
Rat 500 m	Ratio of rats captured in 500-m radius of trap to the number of traps in a 500-m radius within the same time frame	Continuous	Ratio	Trap competition/ patch size
Rat capture	Whether a rat was caught in the same trap within the same time period	Binary	0/1	Relationship
Distance to nearest bush edge	Two-dimensional distance to nearest bush edge (LCDB1)	Continuous	km	Nearest feature
Distance to nearest road	Two-dimensional distance to nearest road	Continuous	km	Nearest feature
Distance to nearest trapping boundary edge	Two-dimensional distance to nearest trapping boundary of study area	Continuous	km	Nearest feature
Stoat irruption	Presence of stoat irruption, Okarito only	Binary	0/1	Relationship

3.4 DATA ANALYSIS

Binary generalised linear models (logistic regression; Hosmer & Lemeshow 2000) were used to determine which large-scale environmental variables (predictors) best explained trap capture success (response) for each stoat control area. Logistic regression uses the method of maximum likelihood to model binary response data, and is suitable for studies when the sampling design is retrospective (Ramsey et al. 1994). The data were explored in two ways: one type of model investigated seasonal effects, and the other annual effects. The soil and climate variables derived from LENZ were used in the annual model because they were of a coarser scale and the annual models contained fewer zeros so were more robust. The annual models also contained only spatially explicit variables with no time elements, so the model results could be mapped as probability surfaces. Since the conclusions that could be drawn from individual models were low inference (Burnham & Anderson 2002), model results from the same type of models and same species were compared across the three stoat control areas to determine which predictor variables were consistent in magnitude and direction between at least two of the control areas.

For each stoat control area, the response variable data were pooled: for the seasonal models, data were pooled by season for each year (i.e. each trap each season); for the annual models, data were pooled into a 'seasonal year' (i.e. spring through to winter of the following year), to reflect the stoats' breeding cycle. Thus, the sample unit for the response variable was each trap for each season (for the seasonal models), and each trap for each seasonal year (for the annual models).

3.4.1 Model selection

Four global models (one seasonal stoat, one annual stoat, one seasonal rat, one annual rat) were constructed for each of the three stoat control areas, making a total of 12 models (six seasonal, six annual). Prior to model fitting for each global model, correlations between predictor variables were checked using the non-parametric Spearman Rank Correlation statistic ρ (rho) (Fowler et al. 1998). Predictor variables with correlations of greater than 0.7 were fitted as single parameter logistic regression models and compared. The variable with the biggest effect size was selected for inclusion in the global model. For each global model, backward stepwise elimination (i.e. sequential removal of the least significant predictor variables from the global model), using the log-likelihood ratio test as the step function (Harraway 1995), was used to select the best model. The log-likelihood ratio test examines the significance (χ^2) of all predictor variables by sequentially removing one predictor variable at a time from the model whilst leaving all others in place. Predictor variables were removed when $P > 0.10$, and re-entered if $P < 0.05$. The resulting models were compared using AIC (Akaike Information Criterion), a penalised version of the likelihood function in which the best model is given by the lowest value (Burnham & Anderson 2002). To determine how good the final model was in an absolute sense, the Hosmer-Lemeshow goodness of fit test (χ^2) was used (Hosmer & Lemeshow 2000). The most parsimonious model with the lowest AIC value and best goodness of fit was selected as the best model.

3.4.2 Spatial mapping

Results from the six final annual models were used to construct spatial probability surfaces (i.e. maps) of stoat and rat capture at each stoat control area. These were constructed using Arcmap 9.1 (ESRI, Redlands, California, USA), with a 25 m × 25 m grid covering each stoat control area.

4. Results

A total of 12 models (six seasonal, six annual) were constructed for the three stoat control areas. The Hosmer-Lemeshow goodness of fit statistic was > 0.05 for 11 of the 12 final models, implying that each model's estimates fitted the data at an acceptable level (Table 3). The only exception was the final seasonal model of the probability of rat capture success at the Okarito stoat control area, which had a goodness of fit statistic with $P < 0.05$, meaning the data did not fit the model at an acceptable level; therefore, the results from this particular model should be interpreted cautiously. Rat capture success was two to three times higher than stoat capture success within each stoat control area (Table 3).

TABLE 3. MODEL SUMMARY STATISTICS FOR STOAT (*Mustela erminea*) AND RAT (*Rattus rattus*) CAPTURE MODELS AT THE THREE STOAT CONTROL AREAS.

For the seasonal model, n = number of traps checked each season; for the annual model, n = number of traps checked each seasonal year (denotes spring through to winter of the following year).

CONTROL AREA	SPECIES	CAPTURES (n)	GLOBAL MODEL	FINAL MODEL		HOSMER-LEMESHOW		
			PREDICTORS (n)	PREDICTORS (n)	DEVIANCE	χ^2	P	df
Seasonal model								
Moehau ($n = 2405$)	Stoat	144	8	6	849.1	12.76	0.12	8
	Rat	582	7	5	2287.3	10.82	0.21	8
Okarito ($n = 9913$)	Stoat	853	9	7	5325.6	13.79	0.09	8
	Rat	2736	8	6	9000.4	52.74	0.00	8
Haast ($n = 4483$)	Stoat	322	8	4	2147.7	4.83	0.68	8
	Rat	681	7	5	3323.2	5.98	0.65	8
Annual model								
Moehau ($n = 1199$)	Stoat	144	12	5	821.2	9.84	0.28	8
	Rat	505	12	6	1545.0	5.58	0.69	8
Okarito ($n = 2644$)	Stoat	729	16	9	2951.7	14.68	0.07	8
	Rat	1472	15	11	2546.5	3.80	0.88	8
Haast ($n = 1274$)	Stoat	273	11	3	1279.1	8.41	0.40	8
	Rat	498	11	5	1456.1	11.60	0.17	8

4.1 SEASONAL MODELS

Table 4 presents the results of the seasonal models for rat and stoat capture probabilities.

4.1.1 Stoat models

At all three of the stoat control areas, stoat capture probability was affected by season. However, seasonal effects differed between the three locations. Relative to winter, stoat capture probability was lower in spring and higher in summer for both Haast and Okarito stoat control areas. Moehau also showed a similar trend with data from only two seasons. Stoat capture probability for autumn (relative to winter) differed between Haast and Okarito, however, being higher for Haast and lower for Okarito. No trapping data were available for autumn and winter from the Moehau stoat control area.

Only two predictor variables were common to all three stoat control areas: increased number of stoat captures at other traps within a 500-m radius around a trap site ('stoat 500 m'), and rat capture at that same trap site during the same period ('rat capture'). Both of these variables increased the probability of future stoat capture at a particular trap site (Table 4). At Moehau and Okarito, decreasing slope increased the probability of stoat capture at a trap site.

The remaining predictors had opposing effect directions, were included in the final model at only one of the stoat control areas, or had no effect on stoat capture probability at any of the areas. Increased altitude had an opposing effect at two of the sites, resulting in decreased probability of stoat capture at Haast, but increased probability of stoat capture at Moehau; and presence of mature forest increased the probability of stoat capture at a trap site at Moehau but decreased the probability of stoat capture at a trap site at Okarito. Increasing easterly aspect of a trap site decreased the probability of stoat capture, but was only included in the model for the Okarito stoat control area. Stoat irruption resulted in increased stoat capture probability during the irruption period (Table 4), but was also only included in the Okarito model. Northerly aspect had no effect on stoat capture probability at any of the areas.

4.1.2 Rat models

The effects of season on rat capture probability also varied between the three stoat control areas (Table 4). At both Haast and Okarito, rat capture probability was much higher in autumn and spring, relative to winter. However, rat capture probability differed between these two stoat control areas in summer, with decreased rat capture probability at Haast and increased rat capture probability at Okarito. The two seasons' data from Moehau were different again, with decreased rat capture probability in spring relative to summer.

Two predictor variables increased the probability of rat capture at all three of the stoat control areas: increasing slope and increased rat captures within a 500-m radius. Increased easterly aspect decreased rat capture probabilities at Haast and Okarito, but increased capture probabilities at Moehau. The presence of forest at a trap site increased the probability of rat capture at Moehau and Okarito.

TABLE 4. ESTIMATED COEFFICIENTS AND STANDARD ERRORS FOR THE PREDICTORS INCLUDED IN THE BEST FIT SEASONAL MULTIPLE LOGISTIC REGRESSION MODELS OF THE PROBABILITY OF STOAT (*Mustela erminea*) OR RAT (*Rattus rattus*) CAPTURE AT THE THREE STOAT CONTROL AREAS.

The shaded boxes denote variables common between locations with the same effect direction; N/A denotes variables not included in the global model; '–' denotes variables included in the global model but excluded from the best fit final model; 'indicator' denotes the season against which other seasons are being compared. Significance level: * = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$.

PREDICTOR VARIABLE	STOAT			RAT		
	MOEHAU	OKARITO	HAAST	MOEHAU	OKARITO	HAAST
Altitude	0.002 ± 0.000***	-	-0.001 ± 0.000***	-	-	-0.003 ± 0.000***
Northerly aspect	-	-	-	-	-	-
Easterly aspect	-	-0.21 ± 0.06***	-	0.13 ± 0.09	-0.076 ± 0.039*	-0.18 ± 0.11
Slope	-0.017 ± 0.008*	-0.012 ± 0.005*	-	0.009 ± 0.004*	0.016 ± 0.003***	0.021 ± 0.005***
Stoat 500m	0.35 ± 0.04***	0.29 ± 0.02***	1.86 ± 0.29***	N/A	N/A	N/A
Rat 500m	N/A	N/A	N/A	0.19 ± 0.02***	0.10 ± 0.01***	1.65 ± 0.15***
Rat capture	0.27 ± 0.20	0.71 ± 0.09***	0.93 ± 0.14***	N/A	N/A	N/A
Forest	0.47 ± 0.28	-0.46 ± 0.10***	-	0.44 ± 0.13***	0.66 ± 0.09***	-
Season						
Winter	N/A	Indicator	Indicator	N/A	Indicator	Indicator
Autumn	N/A	-0.43 ± 0.11***	0.097 ± 0.191	N/A	0.96 ± 0.08***	0.50 ± 0.14***
Spring	-1.97 ± 0.34***	-0.75 ± 0.12***	-0.40 ± 0.18*	-0.46 ± 0.12***	1.13 ± 0.09***	0.11 ± 0.12
Summer	Indicator	0.26 ± 0.10**	0.43 ± 0.15**	Indicator	0.44 ± 0.08***	-0.27 ± 0.13*
Stoat irruption	N/A	0.24 ± 0.08**	N/A	N/A	-1.58 ± 0.07***	N/A
Constant	-3.50 ± 0.30***	-2.41 ± 0.12***	-2.85 ± 0.13***	-2.13 ± 0.15***	-2.19 ± 0.10***	-1.93 ± 0.10***

The remaining predictors were either significant at only one stoat control area or had no effect on rat capture probability at any of the areas. Increasing altitude had a negative effect on rat capture probability at a trap site for the Haast stoat control area, but had no effect at Moehau and Okarito. The presence of a stoat irruption resulted in a corresponding decrease in rat capture probability only at the Okarito stoat control area (Table 4). Northerly aspect had no effect on rat capture probability at any of the areas.

4.2 ANNUAL MODELS

Table 5 presents the results of the annual models for rat and stoat capture probabilities.

4.2.1 Stoat models

The final best fit models differed for each of the three stoat control areas, as no predictor variables for stoat capture probability were consistent across all three models. At Moehau and Okarito, stoat capture probabilities at trap sites increased as soil drainage improved (i.e. soil became drier) and also as trap sites became closer to the operational trapping boundary. All other predictor variables were specific to the final stoat capture probability model for each stoat control area (Table 5).

4.2.2 Rat models

Only one predictor variable was common to the final best fit models for rat capture probability for all three stoat control areas: increasing slope (i.e. steepness) at a trap site increased the probability of rat capture. Three predictor variables with the same effect directions were shared by two of the three stoat control areas, but each was associated with a different combination of control areas: increased soil calcium levels resulted in increased rat capture probabilities at Haast and Okarito; increased soil drainage (i.e. less waterlogged soil) resulted in decreased probability of rat capture at Moehau and Okarito; and increasing distance of the trap site from the bush edge resulted in increased rat capture probablity at Haast and Moehau.

Easterly aspect and proximity of the trap site to the trapping boundary of the stoat control area also affected trap capture probabilities at two of the stoat control areas, but with opposing effect directions. Increasing easterly aspect of a trap site decreased the probability of rat capture at Haast but increased the probability at Moehau. Increasing distance from a trap site to the nearest trapping boundary reduced the probability of rat capture at Moehau, whereas trap sites further from the trapping boundary had a higher probability of catching a rat at Okarito.

The remaining predictor variables were specific to the final rat capture probability models for each particular stoat control area (Table 5).

TABLE 5. ESTIMATED COEFFICIENTS AND STANDARD ERRORS FOR THE PREDICTORS INCLUDED IN THE BEST FIT ANNUAL MULTIPLE LOGISTIC REGRESSION MODELS OF THE PROBABILITY OF STOAT (*Mustela erminea*) OR RAT (*Rattus rattus*) CAPTURE AT THE THREE STOAT CONTROL AREAS.

The shaded boxes denote variables common between locations with the same effect direction; N/A denotes variables not included in the global model; '–' denotes variables included in the global model but excluded from the best fit final model. Significance levels: $^{*}=P<0.05$, $^{**}=P<0.01$, $^{***}=P<0.001$.

PREDICTOR VARIABLE	STOAT			RAT		
	MOEHAU	OKARITO	HAAST	MOEHAU	OKARITO	HAAST
Annual temperature	N/A	N/A	N/A	N/A	N/A	N/A
Minimum temperature	N/A	–	$0.022 \pm 0.005^{***}$	N/A	–	$0.090 \pm 0.009^{***}$
Annual solar radiation	N/A	N/A	N/A	N/A	N/A	N/A
Winter solar radiation	–	N/A	N/A	–	–	N/A
Rainfall to potential evaporation	N/A	$-0.028 \pm 0.008^{***}$	N/A	N/A	$-0.016 \pm 0.007^{*}$	N/A
Vapour pressure deficit	N/A	$0.051 \pm 0.021^{*}$	N/A	N/A	$0.036 \pm 0.016^{*}$	N/A
Phosphorus	N/A	–	0.24 ± 0.13	–	$-0.36 \pm 0.07^{***}$	–
Substrate age	–	$-0.97 \pm 0.17^{***}$	–	–	$1.81 \pm 0.21^{***}$	–
Calcium	N/A	–	–	N/A	$2.15 \pm 0.85^{*}$	$0.48 \pm 0.21^{*}$
Hardness	–	–	N/A	–	N/A	N/A
Particle size	–	–	N/A	–	$-1.28 \pm 0.16^{***}$	N/A
Drainage	$0.454 \pm 0.129^{***}$	$0.246 \pm 0.066^{***}$	–	$-0.20 \pm 0.08^{**}$	$-0.33 \pm 0.10^{***}$	–
Water deficit	$-0.065 \pm 0.017^{***}$	N/A	N/A	$-0.037 \pm 0.009^{***}$	N/A	N/A
Chemical limitations	N/A	N/A	$-1.95 \pm 0.75^{**}$	N/A	N/A	–
Slope	$-0.017 \pm 0.007^{*}$	–	–	$0.011 \pm 0.005^{*}$	$0.017 \pm 0.007^{*}$	$0.018 \pm 0.009^{*}$
Altitude	N/A	$0.004 \pm 0.001^{***}$	N/A	N/A	N/A	N/A
Northerly aspect	–	-0.11 ± 0.07	–	–	-0.135 ± 0.075	–
Easterly aspect	–	$-0.20 \pm 0.07^{**}$	–	$0.22 \pm 0.10^{*}$	–	-0.26 ± 0.15
Distance to nearest trapping edge	$-0.083 \pm 0.037^{*}$	$-0.28 \pm 0.05^{***}$	–	$-0.11 \pm 0.02^{***}$	$0.13 \pm 0.05^{**}$	–
Distance to nearest bush edge	-0.26 ± 0.19	N/A	–	0.25 ± 0.13	N/A	0.28 ± 0.17
Distance to nearest road	–	$-0.10 \pm 0.04^{**}$	N/A	–	–	N/A
Stoat irruption	N/A	–	N/A	N/A	$-2.80 \pm 0.11^{***}$	N/A
Constant	$-2.81 \pm 0.64^{***}$	1.29 ± 1.00	-0.70 ± 0.60	$0.98 \pm 0.38^{**}$	$2.52 \pm 1.07^{*}$	$-3.53 \pm 0.44^{***}$

4.3 SPATIAL MAPPING OF ANNUAL MODELS

The probability of stoat and rat capture was mapped for all three of the stoat control areas (Fig. 2) using the six final best fit annual models (Table 5).

4.3.1 Moehau

At the Moehau stoat control area, the spatial prediction surfaces for stoat (Fig. 2A) and rat (Fig. 2B) capture probability were similar, in that the probability of capture success for both species appeared to increase with altitude. However, neither altitude nor minimum temperature are included in the Moehau models. Instead, it is likely that this model result is driven directly or indirectly by some aspect of soil quality. Both soil drainage and water deficit are significant drivers of the Moehau rat and stoat final models (Table 5). Increasing water deficit decreases the probability of both rat and stoat capture success, while increasing drainage decreases the probability of rat capture success and increases the probability of stoat capture success.

4.3.2 Okarito

The probability of rat and stoat capture was much higher at Okarito than the other two stoat control areas, as reflected in the numbers of captures recorded at the three stoat control areas (Table 3). However, it should be noted that trapping effort was also greater at Okarito (Table 1). Unlike the other two stoat control areas, at Okarito stoat (Fig. 2C) and rat (Fig. 2D) capture spatial prediction surfaces were in reverse to each other across the landscape.

For the stoat annual model, stoat capture success significantly increased with increasing altitude, decreasing easterly aspect, increasing vapour pressure deficit, decreasing substrate age, decreasing rainfall to potential evaporation and increasing drainage (i.e. on dry ridges with good soil fertility characteristics) (Table 5). Reduced distance from roads and the operational trapping boundary also increased stoat capture success (Table 5), as checking effort was more frequent and there was likely to be more invasions by stoats from outside the stoat control area at these trap sites.

In contrast, rat capture probabilities increased with decreased drainage, soil particle size and acid soluble phosphorus, and increased soil age (i.e. on wetter sites with lower soil fertility characteristics) (Table 5). The probability of rat capture success also increased with increasing distance from the trapping boundary.

4.3.3 Haast

The Haast stoat (Fig. 2E) and rat (Fig. 2F) capture probability spatial prediction surfaces generated by their respective final annual models were again similar in appearance. The main driver of both the Haast rat and stoat annual models was minimum temperature (Table 5): increased minimum temperature resulted in increased stoat and rat capture probability. Decreasing minimum temperature is generally correlated with increasing altitude, even though altitude was not included in these models, explaining the apparent increasing rat and stoat capture probabilities with decreasing altitude.

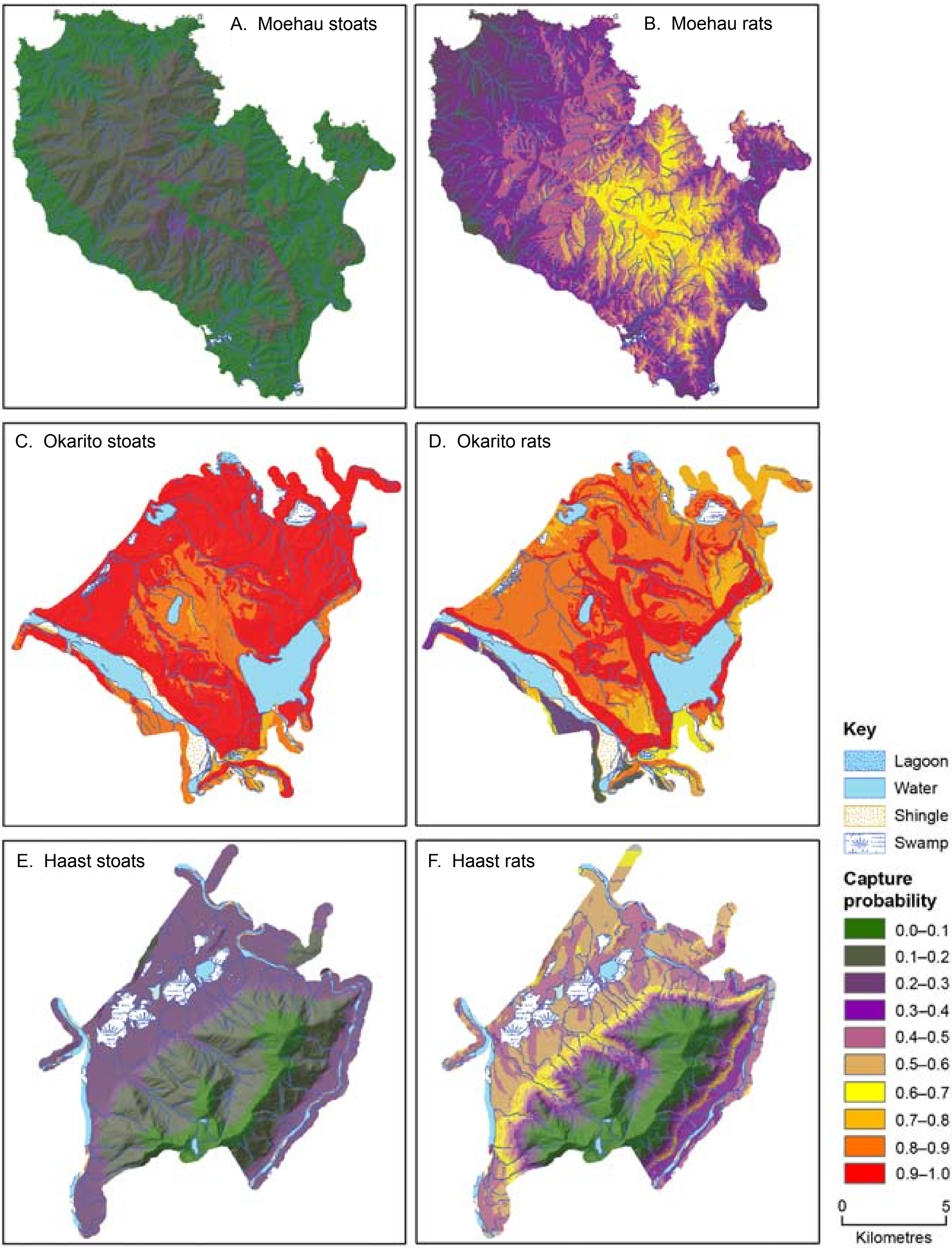


Figure 2. Spatial prediction surfaces of stoat (*Mustela erminea*) and rat (*Rattus rattus*) capture probability generated using the final annual models for the three stoat control areas.

5. Discussion

A number of factors affect stoat and rat capture probabilities. These include food availability, den or nest site location, probability of trap site encounter and capture, population density, and an individual animal's probability of capture. This makes it difficult to make generalised statements about optimal trap placement characteristics. Furthermore, spatial and temporal variation in bait type, trap type, tunnel type and trap checking regime both within and between all three stoat control areas will impact to varying degrees on rat and stoat capture patterns. Consequently, although stoat and rat capture was associated with a number of environmental predictors in this study and a small subset of these had consistent directional effects across all three stoat control areas for each species, the majority varied according to stoat control area and species captured. Therefore, care must be taken when extrapolating the results of these models to other areas where stoat control is either already taking place or is planned. Moreover, the variability of the results emphasises the importance of ensuring that traps are abundant and widespread in stoat control areas.

5.1 ENVIRONMENTAL PREDICTORS OF STOAT CAPTURE

Rat capture at the same trap site during the same season and stoat capture within a 500-m radius showed a consistent directional effect on stoat capture success for all three of the seasonal models. For the annual models, soil drainage and distance from the trapping boundary also significantly affected stoat capture sucess with the same effect direction, but only for two of the three stoat control areas.

At all three stoat control areas, stoat capture was more likely at trap sites where a rat had also been caught that season. Because our data were pooled within year or season for analysis, it was not possible to tease out whether rat and stoat captures occurred in the same trap location over the same trap checking period. However, a more detailed analysis of trapping data from the Hurunui stoat control area revealed that the probability of stoat capture increased if a rat was also caught during the same 2-weekly checking period, although it was not possible to establish which species was caught first (JEC, unpubl. data). There are at least two possible explanations for why rat capture increases the probability of stoat capture at a trap site: rats may act as additional bait and/or both species may occupy similar types of environmental space. Previous investigators have noted the importance of rats as a food source for stoats in mixed podocarp forest ecosystems (King 1982; Murphy & Bradfield 1992; Rickard 1996). It is also possible that the physical placement of particular traps meant that the probability of a stoat or rat encountering that particular trap was higher than usual.

The increased probability of stoat capture at a trap site where stoats had been captured within a 500-m radius that season is indicative of spatial patchiness. Such an aggregation of stoat captures suggests either proximity of a trap site to shared dens by females and their young during the breeding season (Murphy & Dowding 1995; Dowding & Elliot 2003) or, for adult stoats, curiosity about the smell of other stoats in a trap (King & Murphy 2005). Although adult stoats live on separate home ranges for most of the year, home ranges do overlap between sexes, especially when there are high densities of potential prey, such as rats (Murphy & Dowding 1994, 1995; Alterio 1998; Miller et al. 2001). Rat by-catch was relatively high at all three stoat control areas, suggesting overlap of adult stoat home ranges was likely.

At both Moehau and Okarito stoat control areas, increasing drainage (i.e. drier sites) was a significant predictor of capture success. A related study carried out at the same two stoat control areas, but using small-scale microsite predictor variables measured at the trap site, gave similar results (Christie et al. 2006). The higher probability of capturing stoats at trap sites with good soil drainage may be driven by thermoregulation requirements and food availability. Stoats require warm, dry den sites (King 1989) and therefore should be expected to avoid wet, low-drainage areas. Soil drainage also reflects soil fertility (Leathwick et al. 2003), and trap sites with increased fertility are likely to have greater plant productivity and invertebrate richness (Leathwick et al. 2003); invertebrates are an important food source for stoats (King 1982; Murphy & Bradfield 1992; Rickard 1996; Smith & Jamieson 2003).

The finding that increased proximity to the trapping boundary increases stoat capture probability is not unexpected. Trapping boundaries at both the Moehau and Okarito stoat control areas were placed along forest margins for ease of access for checking. These traps could have had higher stoat capture probabilities both because they were checked more frequently and because they were along the trapping boundary, so there would have been more animals available to catch. This also suggests that data from single/double line trapping operations running along valley floors are probably not suitable for this type of exploratory modelling analysis, as these lines generally run along the forest edge, are in close proximity to a river or road, and the trap line is also the trapping edge. Consequently, any such analysis would be confounded by all of these effects, making the results difficult to interpret.

Differences in significant environmental predictors influencing stoat capture between the three stoat control areas are probably best explained by the large variation in environment and landscape composition between the areas. It is likely that a suite of environmental predictor variables are important to stoats because of their flexible and opportunistic feeding strategy (King & Murphy 2005), and that combinations of these will differ in importance according to location (Baldwin et al. 2004). This may explain why environmental predictors that are traditionally thought to influence stoat capture, such as altitude, minimum temperature, distance to bush edge and northerly aspect, were only included in the final models for some, not all, of the stoat control areas.

Differences in latitude and topography between the three stoat control areas may also have had an effect. Haast and Okarito are located at more southerly latitudes than Moehau, and consequently experience much colder temperatures, especially over winter. At a maximum altitude of only 500 m a.s.l., minimum temperatures at Okarito are probably not as severe as Haast, which reaches 1470 m a.s.l. Therefore, it is not surprising that lower minimum temperatures decreased the probability of stoat capture at Haast, but not at Moehau and Okarito. Although stoats are present in cold and snowy environments in the Northern Hemisphere, the wet climate of New Zealand's west coast may make survival at low temperatures more difficult.

5.2 ENVIRONMENTAL PREDICTORS OF RAT CAPTURE

The probability of rat capture success was associated with a larger number of environmental predictors than for stoats. Again, there was variation between the three stoat control areas, but overall a larger number of predictor variables had a consistent directional effect at all three stoat control areas (e.g. slope, rat capture within a 500-m radius, and season) or at two of the three stoat control areas (e.g. easterly aspect, presence of forest, soil calcium, drainage, and distance to bush edge). A related study at two of the same stoat control areas using variables measured at the actual trap site but on a microsite (i.e. local) scale also noted the importance of slope to rats (Christie et al. 2006), and King et al. (1996) found that traps set on warmer, steeper sites caught more rats than traps at other sites. Several investigations have noted that ship rats tend to live in family groups (Hooker & Innes 1995; Innes 2005) and often den together and forage in close proximity (Dowding & Murphy 1994). Therefore, aggregations of captures are not unexpected. However, it should be noted that ship rats were a by-catch species in the stoat traps in this study, where traps were spaced at 200-m intervals, the optimum distance for stoat capture (Dilks et al. 1996; Lawrence & O'Donnell 1999). As ship rat home ranges are less than 200 m in length in podocarp forest (Dowding & Murphy 1994; Hooker & Innes 1995), traps in this study could not be expected to control rats. Captures of rats in neighbouring traps may not, therefore, signify aggregation, but rather the widespread nature of ship rats in that particular environment.

Previous investigators have noted that ship rats tend to be more abundant in podocarp/broadleaved forest than in successional habitat types such as lake margins, grasslands and roadsides (Dowding & Murphy 1994; King et al. 1996; Blackwell et al. 1998; Harper et al. 2005; Christie et al. 2006). Ship rats are capable of occupying disturbed vegetation (Downes et al. 1997; Lehtonenn et al. 2001), but studies both in New Zealand and other countries have noted that forest is generally selected when a mosaic of macro-habitats is available (Cox et al. 2000). Ship rats are arboreal, omnivorous generalists (Innes 2005). It is likely that podocarp forest provides ship rats with a couple of major benefits: greater food availability from the fruiting broadleaved species and invertebrates present (Murphy & Maddigan 2003; Innes 2005; McQueen & Lawrence 2008; Murphy et al. 2008), and suitable trees for nesting (Dowding & Murphy 1994; Innes 2005). Soil calcium, soil drainage and easterly aspect are factors affecting soil fertility and vegetation type (Leathwick et al. 2003). Older soils with poor drainage and high calcium levels are likely to provide poor growing conditions for plants, with specially adapted species such as kahikatea (*Dacrycarpus dacrydioides*) and rimu (*Dacrydium cupressinum*) being dominant (Leathwick et al. 2003). However, high soil calcium levels may slow the process of soil acidification, allowing these sites to support a wider range of plant species (Leathwick et al. 2003). Therefore, it is not surprising that ship rat capture probabilities are positively associated with forest.

As with stoats, it is likely that a suite of environmental predictors are important to ship rats, but with differing combinations according to location. Previous investigators noted that certain small-scale habitat predictors provided cues for determining large-scale habitat use for ship rats (Morris 1987; Cox et al. 2000). However, identifying these small-scale habitat cues can be difficult, as there is considerable variation between sites inhabited by rats. For example, Cox et al. (2000) noted the importance of complex sites with deep leaf litter for ship rat occurrence in a forested habitat, but Harper et al. (2005) found no effect of leaf litter when trapping in podocarp forest on Stewart Island/ Rakiura. Kiekie (*Freycinetia banksii*) and gahnia (*Gahnia* spp.) were also found to be important predictors of ship rat occurrence in some podocarp forests (King et al. 1996; Christie et al. 2006), yet these small-scale predictors are not necessarily present in different forest types at other locations.

5.3 APPLICABILITY OF SPATIAL PREDICTION SURFACES

The spatial prediction surfaces (maps) of the probability of stoat and rat capture success help to make the statistical models more interpretable to a wider audience, especially with regard to making comparisons between the different control areas and species. In terms of the scientific relevance and potential usefulness of the spatial prediction surfaces as management tools, these types of models are probably more relevant at a larger scale, for 'big picture' identification of stoat or rat control areas and timing of control effort.

Each map in Fig. 2 shows capture probabilities for stoats or rats over an entire stoat control area. However, these maps should be interpreted cautiously, as trap sites were not evenly distributed within a stoat control area and data were lacking from many sites within the stoat control area. The maps also fail to identify predictors that will operate at a smaller, local scale (i.e. at the trap site), many of which were unable to be taken into account (e.g. local vegetation species diversity, density of vegetation, visual openness of trap site). These small-scale predictors probably account for a considerable amount of the variation in stoat or rat capture probabilities.

5.4 ASSESSMENT OF THE DATA EXPLORATION TECHNIQUE

It is easy to overestimate the value of data collected for another purpose, such as the trapping data from the stoat control areas used in this study, because the costs of using this appear relatively low compared to collecting new data at additional expense. However, a large quantity of time was needed to convert the trapping data into a useable format. There was a large amount of inherent bias present, such as spatial and temporal variation in trap density, bait type, trap type, tunnel type and trap checking regime, both within and between all three stoat control areas. This variation in trapping effort affects both the capture rate and distribution of captures (King 1980; McDonald & Harris 1999, 2002) and is difficult to tease out. Furthermore, the exploratory nature of the models means that individually our confidence in the conclusions that can be drawn from each model are low inference (Burnham & Anderson 2002). Therefore, although these data appears relatively cheap to collect, there is both a financial cost and model inference cost.

While this study gained some insights into previously unknown environmental variables associated with stoat or rat capture, we advise careful consideration of the above caveats before attempting to use trapping data from control operations for this type of exploratory data analysis in future. Instead, we recommend using data that have been collected in a standardised manner and/or using a designed framework, such as data from the Department of Conservation stoat and rodent tracking tunnel line network (C. Gillies, Research and Development Group, Department of Conservation, unpubl. data).

6. Conclusions

The following conclusions can be drawn from this exploratory modelling project:

- The environmental predictors driving stoat and rat capture probability differed according to the location of the stoat control area, with only a small number of predictor variables common for each species between the control areas.
- The rat models had a larger number of significant environmental predictors with a consistent directional effect between at least two of the control areas than the stoat models.
- Rat capture at the same trap site during the same season and stoat capture within a 500-m radius both increased the probability of stoat capture success at all three stoat control areas using the seasonal models. From the annual models, increasing soil drainage and proximity to trapping boundary both significantly increased the probability of stoat capture success, but at only two of the three stoat control areas.
- Increasing probability of rat capture success was associated with increasing slope, rat capture within a 500-m radius, and season at all three control areas; and with decreasing easterly aspect, presence of forest, increasing soil calcium, decreasing soil drainage, and increasing distance from bush edge at two of the stoat control areas.
- There was a large amount of inherent bias present within the trapping dataset used in this study, which makes interpretation and direct comparisons of model results both within and between the three stoat control areas difficult.
- Spatial predictions of stoat/rat abundance (in the form of maps) will be more useful on a larger scale (i.e. regional, nationwide) than at a local scale to target locations for increased control effort.

7. Recommendations

Based on the models and this report, the authors make several recommendations for conservation management and future research.

7.1 CONSERVATION MANAGEMENT

- Stoat control operations should continue to ensure that traps are abundant and widespread given the variability in the models.
- Changes in stoat and rat control management regimes should be based on the findings from their particular location where possible.

7.2 FUTURE RESEARCH

- A designed framework with specific hypotheses (as opposed to exploratory data analyses) should be used to investigate the environmental predictor variables identified as common between all three stoat control areas in this study. Further research specifically designed to disentangle these effects should focus on the variables identified as common between all stoat control areas in this study.
- Future research should investigate whether rats captured in double trap sets act as additional bait for stoats. This would also have immediate, practical benefits for stoat control areas.
- Rat and stoat footprint tracking data collected by the Department of Conservation from standardised tracking tunnel monitoring lines should be used to develop regional and/or nationwide models of stoat and rat distribution in relation to season, habitat and environmental factors.

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