Abundance of rats (*Rattus* species) following brushtail possum control operations on the Otago Peninsula

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Summary

Project and client

- Brushtail possums (*Trichosurus vulpecula*) and rats (ship rats *Rattus rattus* and Norway rats *R. norvegicus*) are often managed as pests in New Zealand because of their impacts on indigenous species and because possums carry bovine tuberculosis. Research in North Island forests has shown that removal of possums may lead to increased numbers of ship rats, which compete with possums for food.
- The Otago Peninsula Biodiversity Group (OPBG) began removing possums from consecutive sectors of the Otago Peninsula, South Island, in 2011. Later that year they established a network of inked footprint-tracking tunnels to test for changes in rat abundance on the peninsula. This report describes the analysis of 5 years of quarterly rat-track data used as an index of rat abundance (ship rats and Norway rats, collectively), and the results and conclusions from that analysis.

Objectives

- To test for a change in the abundance of rats since possum control was implemented on the Otago Peninsula.

Methods

- In 2011 the OPBG established 10 lines of inked footprint-tracking tunnels on the Otago Peninsula, each with 10 tracking tunnels separated by 50 m. Three additional lines of tracking tunnels were added in 2015. Most lines of tunnels were located in a part of the peninsula (sector 4) where possum control began in 2013. Two lines were placed where possum control had already been done earlier in 2011 (sectors 2 and 3). Every 3 months, inked cards were placed in baited tunnels, removed the next day, and checked for footprints.
- A statistical model was used to test whether the proportion of tunnels per line in which rat tracks were recorded on each monitoring occasion was related to weeks since possum control. The model also included weeks as a quadratic term (to test for a possible curved pattern; e.g. increasing rat numbers followed by stability), as well as the variables season, elevation and presence of grazing livestock.

Results

- On average 10.1% of tunnels had rat tracks, across all lines and all sampling occasions.
- The proportion of tunnels per line that had rat tracks was not significantly related to the number of weeks since possum control ($P > 0.1$). The other explanatory variables in the model were also not statistically significant.

Conclusions

- There has been no detectable increase in rat abundance in more than 5 years since the OPBG implemented rodent tracking in association with possum removals on the Otago Peninsula.
- There was considerable variation in the percentage of inked tunnels tracked by rats, both between lines of tunnels and between monitoring occasions. Differences between the lines may have been the combined result of variation in habitat, surrounding land use, and pest control by landowners.

Recommendations

- The collection and analysis of rodent tracking data has been a major OPBG sub-project, requiring extensive volunteer time and purchases of materials. In addition to testing for a rat population response to possum removal, the work has expanded public knowledge and awareness of the presence of both predatory mammals and indigenous lizards on the peninsula.
- The OPBG can now consider whether funds and volunteer time could usefully be reassigned to other goals.

1 Introduction

Brushtail possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*) are common, widespread, introduced mammals in New Zealand. Norway rats (*R. norvegicus*) are also found throughout New Zealand, but with a patchier distribution (Innes 2005a). Possums and rat species are often managed as pests because of their impacts on indigenous species and because possums carry bovine tuberculosis (Cowan 2005; Innes 2005a, b). Possums feed on the foliage, flowers and fruit of forest and garden plants, and prey on invertebrates and on birds and their eggs (Cowan 2005). Ship rats and Norway rats eat fruit, seeds and other plant parts, and prey on invertebrates, bird eggs and chicks, and lizards (Innes 2005a, b).

Ship rats have been identified as one of the most important nest predators in urban and peri-urban environments, and in forest fragments (van Heezik et al. 2008; Morgan et al. 2011; Innes et al. 2015). Controlling ship rats or both ship rats and possums can benefit birds in North Island forest fragments (Armstrong et al. 2014; Innes et al. 2015). However, controlling only a subset of interacting invasive species can have unexpected consequences for other species that are their competitors, prey or predators (e.g. Ruscoe et al. 2011; Norbury et al. 2013). This report describes monitoring for any changes in the abundance of rat species as a consequence of widespread removal of possums.

2 Background

The Otago Peninsula Biodiversity Group (OPBG) began removing possums from the Otago Peninsula (henceforth ‘the peninsula’) in 2011. Research in the North Island has shown that after possums and rats are removed with aerial toxin drops, ship rats may increase to higher numbers than at non-treatment sites where toxin was not applied (Ruscoe et al. 2011; Griffiths & Barron 2016). These increases are thought to occur because with fewer possums present, more food is available to ship rats, which compete with possums for food (known as competitive release; Sweetapple & Nugent 2007; Ruscoe et al. 2011).

The OPBG wanted to test for a similar increase in rat populations (ship rats and/or Norway rats) as a consequence of possum removal on the peninsula. Therefore, in order to detect changes in rodent activity, they established a network of inked footprint-tracking tunnels on the peninsula in 2011. Rodents have been monitored quarterly on this tunnel network, beginning in November 2011 and with the most recent monitoring completed in February 2017. In 2016 the OPBG obtained funding from the Otago Regional Council’s Environmental Enhancement Fund for this analysis of the resulting rat-track data.

3 Objectives

The purpose of this analysis was to test for a change in the abundance of rats since possum control was implemented on the peninsula. The proportion of inked footprint tracking tunnels containing rat tracks was used as an index of rat abundance. This index actually measures rat activity, not abundance, as individual rats are not identified. Therefore standard methods were followed (see Gillies & Williams 2013) to minimise variation in factors (such as weather) that affect only activity and not abundance. It is not possible to distinguish rat species (ship rats vs Norway rats) from their footprints.

4 Methods

4.1 Study site

The Otago Peninsula (centred near 45°52'S, 170°40'E) is c. 20 km long and up to 9 km wide. Its southwestern end adjoins the mainland in a 1.5 km-wide isthmus. Although part of Dunedin City, it is sparsely populated, with most small communities located on its northwestern shore along the Otago Harbour. The land is dominated by steep, open pasture, with pockets of indigenous shrubs and forest, and exotic trees planted for fruit, shelter or forestry.

Possums were removed progressively from four sectors of the peninsula, beginning in the north and east, and proceeding southwest towards the isthmus in the suburbs of Dunedin city (for a sector map, see www.pestfreepeninsula.org.nz). The main possum 'knockdown' operations in sectors 1–3 were done from March to June 2011, and in sector 4 from December to April 2013. These operations were followed by 'mop-up' and 'hot-spot' possum removals that still continue. Control operations have used a combination of toxins (in bait stations) and traps.

4.2 Tracking tunnel lines

The OPBG established 10 lines of inked footprint-tracking tunnels on the peninsula in October 2011 and began using them to monitor rats in November 2011 (Fig. 1). The lines followed walking tracks, fences or gullies, in places with indigenous or exotic trees, shrubs and/or dense ground cover, including rank grass, ferns or bidibids (*Acaena* spp). Most lines were separated by more than 300 m, but one pair of lines was only 64 m apart at their closest point (Hereweka and Leith Walk). Each line comprised 10 tracking tunnels separated by 50 m, according to Department of Conservation guidelines (Gillies & Williams 2013). Lines were established in both the presence (three lines with grazing at eight or more tunnels per line) and absence (seven lines) of livestock, because grazing was expected to reduce rodent activity (Knox et al. 2012). The grazed lines were Bacon Street, Marine Station and Sandymount Shrubland.

Eight lines were placed in sector 4 prior to the possum knockdown operation there (December–April 2013). One line was placed in sector 2 and one in sector 3, where possums had already been removed (knockdown operations in May and June 2011, respectively). These sector 2 and 3 locations were chosen for comparison with the results of tracking tunnel monitoring in a previous study (2009/10; Knox et al. 2012), and include an ungrazed and a grazed line. However, because of small differences between the OPBG's tracking tunnel protocol (below) and that of Knox et al. (2012), the earlier data from 2009/10 were not included in the statistical analysis described here.

Three additional lines of tracking tunnels were established by the OPBG in ungrazed locations in sector 4 in February 2015 (Fig. 1), in order to increase the sample size for detection of changes in rodent tracking rates. An additional tunnel line operated by the environmental group Save The Otago Peninsula (STOP) is not considered here because rat control is carried out in its vicinity.

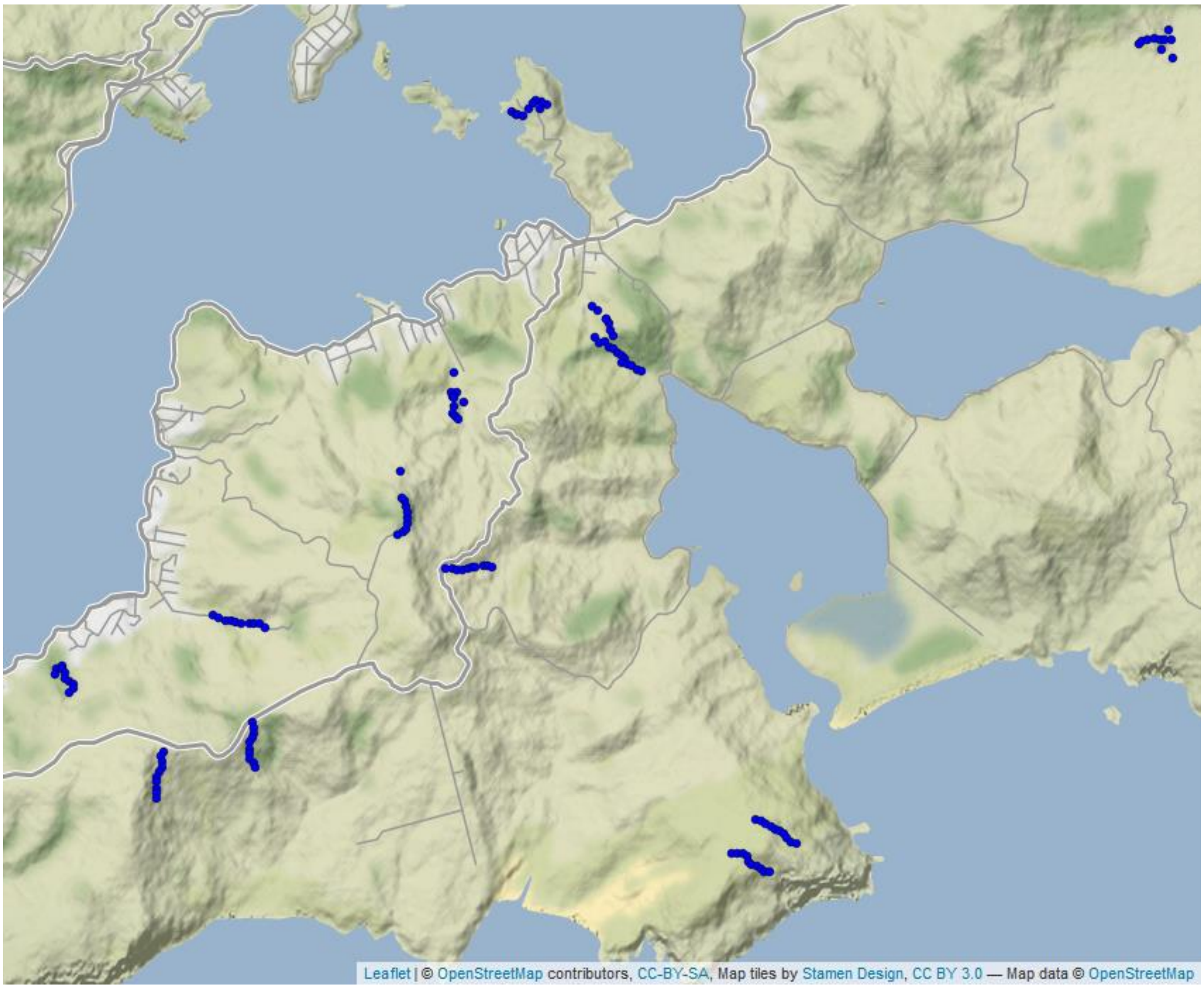

Figure 1 Lines of inked footprint-tracking tunnels used for rodent monitoring on the Otago Peninsula from 2011 to 2017. From north to south, the lines are known as Pyramids (sector 2), Marine Station (sector 3), Hereweka, Leith Walk (the latter two lines are close together), Bacon Street, Camp Road, Stewarts Creek, Greenacres, Glenfalloch, Paradise, Buskin, Sandymount Macrocarpa and Sandymount Shrubland. All lines except the two northern-most are in sector 4. Ten lines were established in October 2011, and Greenacres, Glenfalloch and Buskin were added in February 2015. Map copyright information is at www.openstreetmap.org/copyright. Sector map is at www.pestfreepeninsula.org.nz. For scale, each line of tunnels is c. 450 m long.

4.3 Tracking tunnel protocol

The design of the tracking tunnels and the protocol for operating them followed Gillies & Williams (2013). Tracking tunnels (615 × 100 × 100 mm) were made from black plastic (Corflute) with wooden bases. Every 3 months, when little or no overnight rain was forecast, volunteers placed an inked card (Gotcha Traps, Warkworth) in each tunnel and baited the tunnel with peanut butter smeared at each end. Cards were checked and removed the next day. Volunteers identified animal footprints with the aid of Ratz (1997), Agnew (2009), Gillies & Williams (unpublished), and expert opinion (from G. A. Pickerell, University of Otago, pers. comm.).

4.4 Analytical methods

A statistical model was fitted to the rat-tracking data. The type of model used was a generalised linear mixed-effects model for binomial data (with a logit link function). The response variable was the number of successes (rat detections) given the number of independent trials (tunnels) on each line on each occasion. Tunnels that were missing, overturned or had tracking cards pulled out (probably by possums) were omitted from the analysis.

A variable 'line' identifying the different lines of tunnels was fitted as a random effect to account for repeatedly monitoring the same locations instead of establishing new tunnel lines at each monitoring occasion. This variable estimated consistent differences over time in tracking probability between the lines. These differences might arise from local vegetation type, surrounding land use, pest control by landowners, and other unmeasured factors affecting rat distribution and abundance around each line.

The main explanatory variable of interest was the number of weeks since possum control, based on completions of the main knockdown operations (31 May 2011, 30 June 2011 and 30 April 2013 in sectors 2, 3 and 4, respectively). After rat populations in the Tararua Range (North Island) were reduced to low levels by aerial poisoning, the pattern of rat-tracking data suggested exponential population growth (i.e. linear growth, on a logarithmic scale) for 2.5 years, which then levelled off (Griffiths & Barron 2016). These authors therefore restricted their analysis to this initial 2.5 years of data.

Such a pattern was not obvious in rat-tracking data from the peninsula, where rat populations were not reduced by the ground-based possum control. Therefore, I added a quadratic term (weeks^2) to the model to allow for a curved relationship between tracking rates and weeks since control, which could result from an increasing rat population followed by stability or decline. Function poly in R (R Core Team 2016) was used to calculate orthogonal (i.e. independent) linear and quadratic explanatory variables so that the quadratic term would account only for variation not already explained by the linear 'weeks' term.

Additional explanatory variables fitted as fixed effects were season (spring, summer, autumn and winter, corresponding to November, February, May/June and August), the mean elevation of the tracking tunnel locations on each line (as in Griffiths & Barron 2016), and the presence or absence of livestock grazing (as in Knox et al. 2012) on the line (at eight or more tunnels). I evaluated whether a classification of lines by vegetation type, based on the New Zealand Land Cover Data Base (LCDB version 4.1), could be used as an explanatory variable. However, this was not suitable because some classes were not replicated between lines of tunnels; i.e. one line was dominated by each of the classes low producing grassland, mixed exotic shrubland, and mānuka and/or kānuka. Prior to analysis I rescaled elevation to have mean 0 and standard deviation 0.5 by subtracting the mean and dividing by two standard deviations in order to improve numerical stability. The R function 'poly', described above, also rescaled the variables weeks and weeks^2.

This binomial model relied on the assumptions that each tunnel had an equal probability of being tracked by a rat and that tunnels were independent of each other. As discussed above, the model's random line effect accounted for differences in tracking probability between lines of tunnels. However, because the tunnels within a line were only 50 m apart and ship rats and Norway rats range much further (Innes 2005a, b), tunnels that were close together were probably not independent (see also Griffiths & Barron 2016).

This problem can lead to over-dispersion (i.e. excess variance not accounted for by the model, which can bias the statistical analysis). I accounted for over-dispersion by adding an observation-level random effect (i.e. fitting an additional normally distributed error term for each observation; Browne et al. 2005). This additional effect was included after testing whether it improved the model, based on Akaike's information criterion adjusted for small samples (AIC_c; Burnham & Anderson 2002), computed in the MuMIn package for R (Bartoń 2016).

An explanatory variable was considered statistically significant ($P < 0.05$) if the 95% highest posterior density interval (HPDI) of its model coefficient excluded zero. I used these intervals because the usual method of estimating 95% confidence intervals (CI) is not straightforward for mixed-effects models. All HPDI were calculated from 1,000 draws from the posterior distribution for each of the estimated fixed effects, using the HPDinterval function in the coda package for R (Plummer et al. 2006).

Two lines of tunnels (Hereweka and Leith Walk) were not independent. A single individual rat could potentially track tunnels on both lines, which were separated by only 64 m (see above), which is less than the typical home range lengths of ship rats and Norway rats (Innes 2005a, b). To test how this non-independence affected the statistical results, I used a separate model with data omitted from two tunnels on each of these lines, so that the resulting two eight-tunnel lines were separated by ≥200 m, as recommended in Gillies & Williams 2013.

Marginal R^2 (variance in the data explained by the explanatory variables [fixed effects] in the model) and conditional R^2 (variance explained by both fixed and random effects) are provided as measures of model goodness-of-fit (Nakagawa & Shielzeth 2012). Models were fitted in the lme4 package (Bates et al. 2015) in R version 3.3.0 (R Core Team 2016).

5 Results

On average, 10.1% of tunnels had rat tracks, across all lines and all sampling occasions (±0.8% standard error [SE]). During most of the study the average percentage of tunnels with rat tracks on each line varied between 5 and 22% in sector 4, and between 0 and 15% in sectors 2 and 3 combined (Fig. 2). The average in sectors 2 and 3 reached 36% on the most recent sampling occasion in February 2017, owing to a 50% tracking rate at Marine Station, which was not extreme compared with previous results on other lines (Fig. 3). Tunnels also recorded footprints of possums, house mice (*Mus musculus*), European hedgehogs (*Erinaceus europaeus*) and indigenous lizards (presumed to be skinks *Oligosoma* spp. and kōrero geckos *Woodworthia* sp. 'Otago large'; Knox 2016).

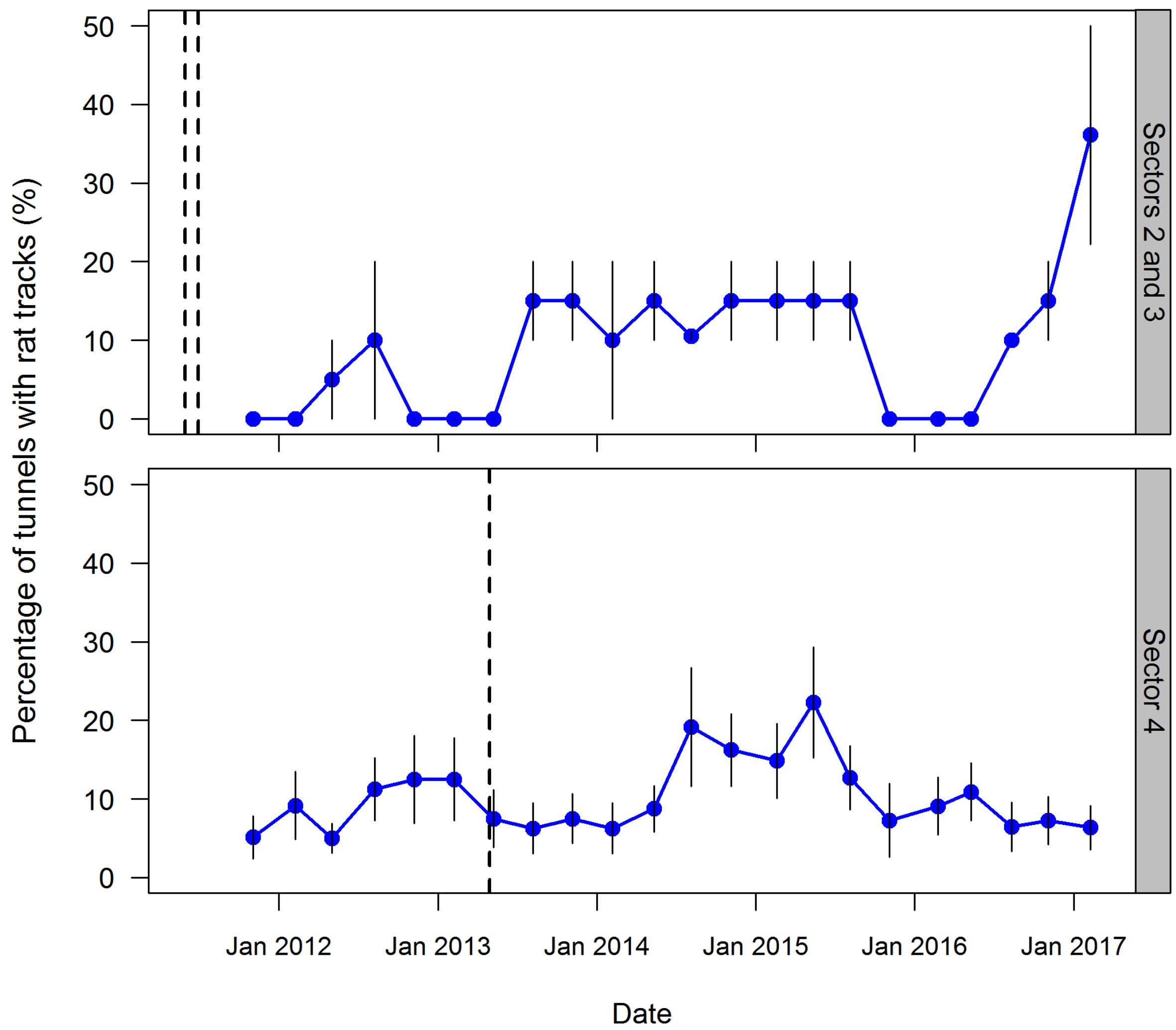

Figure 2 Mean percentage of tunnels with rat tracks on lines of tunnels in sectors 2 and 3 combined (Pyramids and Marine Station lines) and in sector 4 (all other lines) from November 2011 to February 2017. The dashed lines show the dates of possum knockdown operations in each sector. Error bars indicate standard errors (SE).

The proportion of tunnels per line that were tracked by rats was not significantly related to the number of weeks since possum control ($P > 0.1$), in either its linear (weeks) or quadratic ($weeks^2$) forms. The other explanatory variables in the model (season, elevation, grazing) were also not statistically significant ($P > 0.1$).

There was considerable variation in rat-tracking rates between the different lines (Fig. 3) due to unmeasured differences between locations. Variation between monitoring occasions was not consistent between seasons (Fig. 3). Adding the observation-level random effect improved the model, lowering AIC_c by 3.2 units. The model explained only 23% of variation in the data without including random effects of line and observation (i.e. marginal R^2), but 44% of variation when the random effects were included (conditional R^2).

A separate exploratory model, with data omitted from two tunnels on each of the Hereweka and Leith Walk lines so that the lines were at least 200 m apart, gave similar results to those described above. As a result, the non-independence of these two lines did not affect the conclusions.

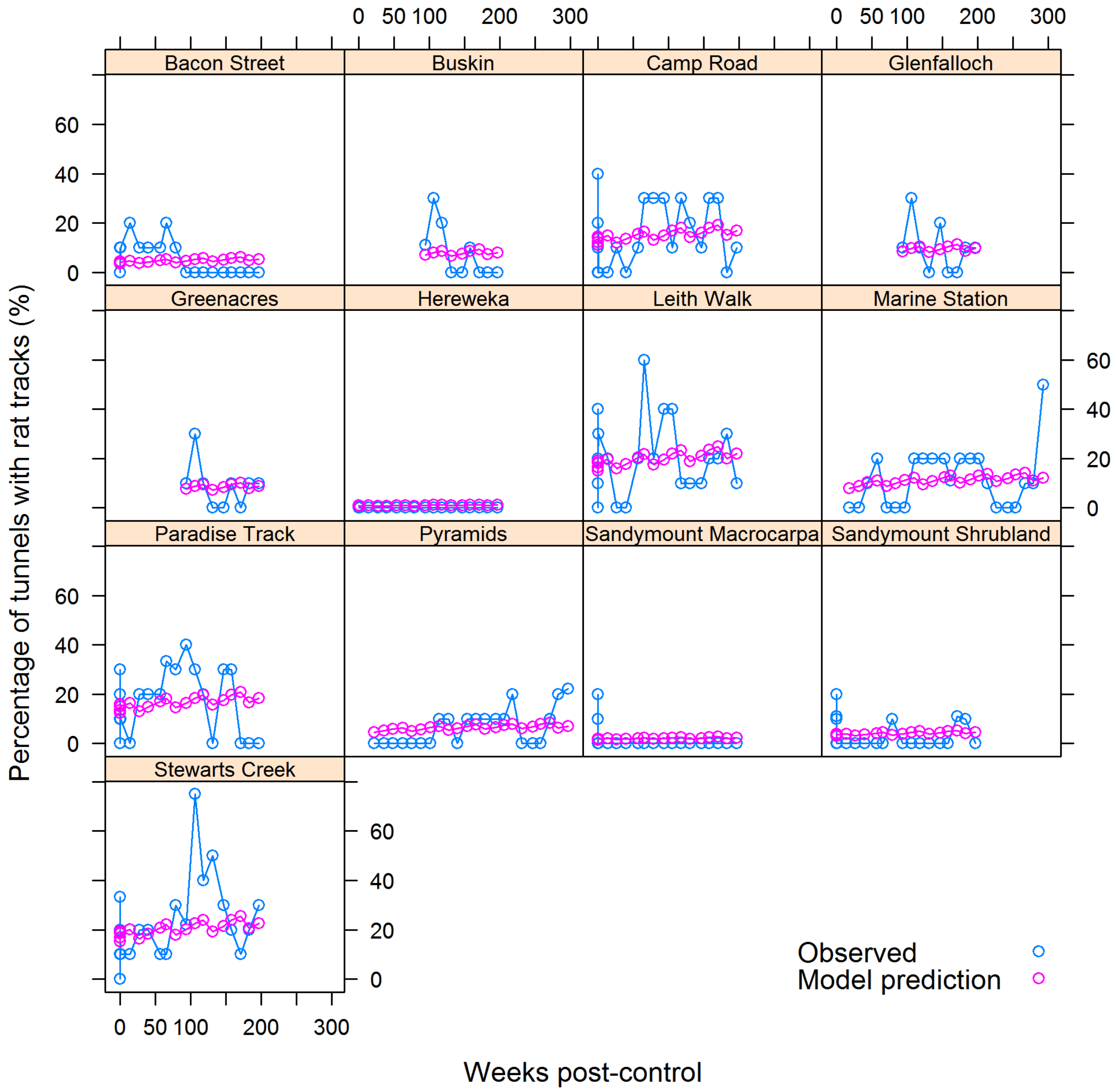

Figure 3 Percentage of tunnels tracked by rats on each line of tracking tunnels, both observed (blue) and predicted by the fitted statistical model (pink). Although the model predicted an increasing probability of rat tracks as a function of weeks since possum control, this positive slope estimate did not differ significantly from zero. Model predictions shown here include random line effects but not random observation-level effects.

6 Discussion and conclusions

6.1 No evidence for a significant rat population increase on the peninsula

The analysis found no evidence that rat numbers have increased since possum control began on the Otago Peninsula. Instead, the percentage of inked tunnels tracked by rats varied considerably between lines of tunnels and between monitoring occasions. There was no strong seasonal pattern: although rat abundance is often highest in May or August after summer breeding (Innes 2005a, b), the average tracking rates peaked at other times in some years. Differences between the lines may have been the combined result of variation in vegetation cover, surrounding land use, and pest control by landowners.

The average rat-tracking rate on the peninsula (c. 10%) was low compared with data from North Island forests (e.g. Sweetapple & Nugent 2011; Griffiths & Barron 2016) and a South Island forest (Murphy et al. 2008). Few South Island standard rat-tracking studies have been published, particularly for patchy landscapes like the peninsula. In an earlier peninsula study, rat-tracking rates in shrubland (*Coprosma* spp.) and regenerating kānuka forest (*Kunzea robusta*; de Lange 2014) averaged <5% in grazed sites and c. 40% in ungrazed sites (Knox et al. 2012). Possibly bait placement in the middle of each tracking tunnel in this earlier study may have elevated tracking rates relative to the OPBG study, with bait placed at tunnel ends (following Gillies & Williams 2013).

Livestock grazing lowers rodent activity and abundance by removing dense ground vegetation, which supplies rodents with shelter and food (Innes et al. 2010; Knox et al. 2012). In the OPBG study, rat-tracking rates often exceeded 20% at Camp Road, Leith Walk, Paradise Track and Stewarts Creek (Fig. 3), all ungrazed locations. It is clear, however, that grazing was not the only factor leading to low rat-tracking rates, as two other ungrazed locations (Hereweka and Sandymount Macrocarpa) had 0% rat tracking on all or most occasions. The lack of a clear effect of grazing in the OPBG study may be the result of variable grazing intensity between lines and over time, or over-riding effects of other habitat elements such as vegetation type.

6.2 Alternative study designs

After both possum and ship rat populations were reduced to low densities by aerial 1080 (sodium fluoroacetate) toxin operations in North Island forests, rat numbers increased to higher levels than at non-treatment sites (indicated by trapping or tracking; Ruscoe et al. 2011; Griffiths & Barron 2016). These experimental studies each had two independent toxin treatment sites and one or more non-treatment sites (Ruscoe et al. 2011; Griffiths & Barron 2016). In the earlier tracking tunnel study, each site had 15–20 lines of tracking tunnels (Griffiths & Barron 2016). These study designs allowed for relatively powerful statistical comparisons between treatment and non-treatment sites.

In contrast, because the peninsula study was not an experimental one, possum control was applied to most of the area, with neither non-treatment nor replicated treatment sites. Sector 5 at the southwest end of the peninsula, where possums have not yet been controlled, was not considered a suitable non-treatment site because of its small area and largely suburban land use. Instead of comparing between sites, the statistical analysis was aimed at detecting changes in peninsula rat-tracking rates over time since the major possum control operations. It proved impossible to identify any long-term temporal trend against the background of other variation between lines, monitoring occasions and years.

In an earlier North Island forest study, average rat abundance (indexed as disturbance of flour-and-icing sugar lures placed for possums) was higher after aerial poisoning than before (allowing 1.5 years for the rat population to recover after the poison operation; Sweetapple & Nugent 2007). The increased rat abundance could not be attributed with certainty to possum removal, because the study was unreplicated and had no non-treatment site (Sweetapple & Nugent 2007). The same limitation would apply to conclusions from the present peninsula project, which has a similar design.

Rat population increases were apparent in the three North Island projects described above, despite variation in the degree to which possum numbers were reduced. Post-control possum numbers were measured in different ways in the three studies, and were summarised as:

- possums per hectare: 25% of non-treatment sites (Ruscoe et al. 2011)
- possum bites on waxtag blocks (Thomas et al. 2003): c. 0% compared with 30% at non-treatment sites (Griffiths & Barron 2016)
- <1 possum capture per 100 trap-nights (Sweetapple & Nugent 2007).

Griffiths and Barron (2016) found an inverse relationship between rat-tracking indices and the percentages of waxtags bitten by possums near tracking tunnel lines. On the peninsula, possum removals are ongoing and some possum hot-spots remain. Chew-cards (Sweetapple & Nugent 2011) used to record possum activity on the peninsula coincide with five tracking tunnel lines. In any future study, chew-cards placed along all tunnel lines from the beginning of the study could help to explain variation in rat-tracking rates.

A final improvement to the design of a future peninsula study would be to restrict tracking tunnel lines to a particular habitat of interest (e.g. ungrazed indigenous forest fragments). This constraint would tend to reduce variation in rat-tracking rates between lines of tunnels.

6.3 Potential for new research

Peninsula bird populations could benefit from rat control in forest patches, in combination with existing possum control. The importance of ship rats as nest predators is best known for the North Island (Morgan et al. 2011; Armstrong et al. 2014; Innes et al. 2015). Relative predation by different mammalian species on birds and their nests has not been studied on the peninsula, but ship rats, possums and possibly house mice were identified as nest predators in urban Dunedin (van Heezik et al. 2008). Using motion-activated cameras to study bird nesting success on the peninsula would show the relative impacts of different predator species on peninsula birds, and would help to establish priorities for future predator management.

The species of rats whose footprints were found in tracking tunnels is not known. Ship rats are the most widespread rat species in New Zealand, living in many habitats including forests, hedgerows, farms, parks and buildings (Innes 2005b). Norway rats are commensal with humans in urban areas and farms; in the wild their distribution is patchy and not well studied, but they are often found in wetland habitats (Innes 2005a). Given the peninsula's patches of forest and shrublands, long coastline, streams, farms and villages, both species may be active in the vicinity of the OPBG's tracking tunnel lines. Differences in their ecology and behaviour could obscure relationships between tracking rates and the variables considered in this analysis (i.e. season, elevation, grazing and time since possum control).

In recent studies in New Zealand cities the ratio of ship rats to Norway rats captured was approximately 90:10 in forest reserves, gullies and parks in Hamilton (Morgan et al. 2009), New Plymouth and Tauranga (Bartlam et al., unpublished). In contrast, the ratio of ship rats to Norway rats was only 25:75 in orchards and farms in the outskirts of Hamilton (Morgan et al. 2011). In these studies, rat traps were placed where tracks in tunnels or chewing on waxtags indicated that rats were present. A similar study on the peninsula (e.g. after the next planned tracking tunnel monitoring in May 2017) would show which rat species predominates and hence which indigenous species are most at risk. For example, ship rats are more arboreal than Norway rats (Innes 2005a, b), and hence more likely to threaten tree-nesting birds and arboreal lizards.

7 Recommendations

There has been no detectable increase in rat abundance in the more than 5 years since the OPBG implemented rodent tracking in association with possum removals on the Otago Peninsula. The collection and analysis of data have been an extensive OPBG sub-project, requiring considerable volunteer time and repeated procurement of tracking cards and bait. In addition to testing for a rat population response to possum removal, this work has expanded public knowledge and awareness of the presence of both predatory mammals and indigenous lizards on the peninsula.

The OPBG can now consider whether funds and volunteer time could usefully be reassigned to other goals. If so, rodent monitoring could be reinitiated in future to test for the effects of new predator control operations (e.g. multi-species control, or possum control in sector 5 where none has yet been attempted). Monitoring rodents at multiple treatment and non-treatment sites, if feasible, would help to detect changes in rodent populations resulting from these new projects. Other design improvements, including restricting rodent lines to a habitat of interest and placing chew-cards along rodent lines as an index of possum abundance, are discussed above.

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9 References

Agnew W 2009. What made these tracks?: a guide to assist in interpreting the tracks of small mammals, lizards and insects. Warkworth, NZ, W. Agnew. 24 p.

Armstrong DP, Gorman N, Pike R, Kreigenhofer B, McArthur N, Govella S, Barrett P, Richard Y 2014. Strategic rat control for restoring populations of native species in forest fragments. Conservation Biology 28: 713–723.

Bartlam S, Innes J, Fitzgerald NB. Inventory of mammalian pests in two New Zealand cities. Unpublished manuscript.

Bartoń K 2016. Package MuMIn: multi-model inference. https://cran.r-project.org/ (accessed 24 March 2017).

Bates D, Machler M, Bolker BM, Walker SC 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67: 1–48.

Browne WJ, Subramanian SV, Jones K, Goldstein H 2005. Variance partitioning in multilevel logistic models that exhibit overdispersion. Journal of the Royal Statistical Society A 168: 599–613.

Burnham KP, Anderson DR 2002. Model selection and multimodel inference: a practical information theoretic approach. New York, Springer-Verlag. 353 p.

Cowan PE 2005. Brushtail possum. In: King CM ed. The handbook of New Zealand mammals. 2nd edn. Melbourne, VIC, Oxford University Press. Pp. 56–80.

de Lange PJ 2014. A revision of the New Zealand *Kunzea ericoides* (Myrtaceae) complex. Phytokeys 40: 1–185. doi: 10.3897/phytokeys.40.7973

Gillies CA, Williams D 2013. DOC tracking tunnel guide v2.5.2: using tracking tunnels to monitor rodents and mustelids. Hamilton, NZ, Department of Conservation, Science & Capability Group. http://www.doc.govt.nz (accessed 22 March 2017).

Gillies CA, Williams D. A short guide for identifying footprints on tracking tunnel papers. Unpublished. http://www.rimutakatrust.org.nz/downloads/Footprints_OLDDM-63018%201%20.doc (accessed 22 March 2017).

Griffiths JW, Barron MC 2016. Spatiotemporal changes in relative rat (*Rattus rattus*) abundance following large-scale pest control. New Zealand Journal of Ecology 40: 371–380.

Innes JG 2005a. Norway Rat. In: King CM ed. The handbook of New Zealand mammals. 2nd edn. Melbourne, VIC, Oxford University Press. Pp. 174–187.

Innes JG 2005b. Ship rat. In: King CM ed. The handbook of New Zealand mammals. 2nd edn. Melbourne, VIC, Oxford University Press. Pp. 187–203.

Innes J, King C, Bartlam S, Forrester G, Howitt R 2015. Predator control improves nesting success in Waikato forest fragments. New Zealand Journal of Ecology 39: 245–253.

Innes J, King CM, Bridgman L, Fitzgerald N, Arnold G, Cox N 2010. Effect of grazing on ship rat density in forest fragments of lowland Waikato, New Zealand. New Zealand Journal of Ecology 34: 227–232.

Knox C 2016. Otago Peninsula lizard monitoring report 2016. Prepared for the Otago Peninsula Biodiversity Group (OPBG). 19 p. http://www.pestfreepeninsula.org.nz/wp-content/uploads/2016/12/Knox-CD-2016-OPBG-Lizard-Monitoring-Report.pdf (accessed 31 March 2017).

Knox CD, Cree A, Seddon PJ 2012. Direct and indirect effects of grazing by introduced mammals on a native, arboreal gecko (*Naultinus gemmeus*). Journal of Herpetology 46: 145–152.

Morgan DKJ, Waas JR, Innes J 2009. An inventory of mammalian pests in a New Zealand city. New Zealand Journal of Zoology 36: 23–33.

Morgan DKJ, Waas JR, Innes J, Fitzgerald N 2011. Identification of nest predators using continuous time-lapse recording in a New Zealand city. New Zealand Journal of Zoology 38: 343–347.

Murphy E, Maddigan F, Edwards B, Clapperton K 2008. Diet of stoats at Okarito Kiwi Sanctuary, South Westland, New Zealand. New Zealand Journal of Ecology 32: 41–45.

Nakagawa S, Schielzeth H 2012. A general and simple method for obtaining R^2 from generalized linear mixed-effects models. Methods in Ecology and Evolution 4: 133–142.

Norbury G, Byrom A, Pech R, Smith J, Clarke D, Anderson D, Forrester G 2013. Invasive mammals and habitat modification interact to generate unforeseen outcomes for indigenous fauna. Ecological Applications 23: 1707–1721.

Plummer M, Best N, Cowles K, Vines K 2006. Coda: convergence diagnosis and output analysis for MCMC. R News 6: 7–11. https://cran.r-project.org/doc/Rnews/Rnews_2006-1.pdf (accessed 22 March 2017).

R Core Team 2016. R: a language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing. https://www.R-project.org/

Ratz H 1997. Identification of footprints of some small mammals. Mammalia 61: 431–441.

Ruscoe WA, Ramsey DSL, Pech RP, Sweetapple PJ, Yockney I, Barron MC, Perry M, Nugent G, Carran R, Warne R, et al. 2011. Unexpected consequences of control: competitive vs. predator release in a four-species assemblage of invasive mammals. Ecology Letters 14: 1035–1042.

Sweetapple PJ, Nugent G 2007. Ship rat demography and diet following possum control in a mixed podocarp–hardwood forest. New Zealand Journal of Ecology 31: 186–201.

Sweetapple P, Nugent G 2011. Chew-track-cards: a multiple-species small mammal detection device. New Zealand Journal of Ecology 35: 153–162.

Thomas MD, Brown JA, Maddigan FW, Sessions LA 2003. Comparison of trap-catch and bait interference methods for estimating possum densities. New Zealand Plant Protection 56: 81–85.

van Heezik Y, Ludwig K, Whitwell S, McLean IG 2008. Nest survival of birds in an urban environment in New Zealand. New Zealand Journal of Ecology 32: 155–165.