

Modelling detectability of kiore (*Rattus exulans*) on Aguiguan, Mariana Islands, to inform possible eradication and monitoring efforts

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Abstract: Estimating the detection probability of introduced organisms during the pre-monitoring phase of an eradication effort can be extremely helpful in informing eradication and post-eradication monitoring efforts, but this step is rarely taken. We used data collected during 11 nights of mark-recapture sampling on Aguiguan, Mariana Islands, to estimate introduced kiore (*Rattus exulans* Peale) density and detection probability, and evaluated factors affecting detectability to help inform possible eradication efforts. Modelling of 62 captures of 48 individuals resulted in a model-averaged density estimate of 55 kiore/ha. Kiore detection probability was best explained by a model allowing neophobia to diminish linearly (i.e. capture probability increased linearly) until occasion 7, with additive effects of sex and cumulative rainfall over the prior 48 hours. Detection probability increased with increasing rainfall and females were up to three times more likely than males to be trapped. In this paper, we illustrate the type of information that can be obtained by modelling mark-recapture data collected during pre-eradication monitoring and discuss the potential of using these data to inform eradication and post-eradication monitoring efforts.

Keywords: absolute density; capture probability; detection probability; mark-recapture; neophobia

Introduction

Toxicant-based eradication has become an increasingly common tool used to manage the impacts of introduced rodents on islands (Howald et al. 2007). As eradication expertise has grown, eradication efforts have been aimed at larger, more remote, and more biologically complex islands, often with great success (Towns & Broome 2003; Howald et al. 2007). One facet of eradication that has lagged behind, however, is our ability to efficiently determine success or failure of a given eradication effort. As noted by Howald et al. (2007), eradication success is often determined by waiting to see if survivors repopulate the island to an easily detectable level, under the assumption that it would be more costly to detect and eradicate a low-density population than to conduct a full-scale eradication at a future date. While it is certainly true that detection and eradication of low-density rodent populations is costly and difficult, this approach may lead to several potential problems. If we assume that individuals surviving the initial eradication attempt are more resistant to toxicant effects and/or less likely to consume toxicant than the majority of the population, then by allowing these individuals to found a new population we are in effect selecting for increased eradication resistance (Pelz et al. 1995). Further, the likely rapid population growth following an unsuccessful rodent eradication (Davis 1953) could in some instances be more detrimental to native fauna and flora than the original, somewhat stable population preceding the eradication attempt. Finally, repeated toxicant-based eradication efforts increase the likelihood of negative impacts on non-target species, either through increased direct exposure to toxicant or bio-accumulation in island trophic systems (Hoare & Hare 2006). Given these potential risks,

there is an urgent need to implement effective and efficient rodent monitoring strategies as a component of eradication planning.

We propose that rigorous pre-eradication mark-recapture monitoring of introduced rodent populations can improve the effectiveness of both eradication and post-eradication monitoring efforts. Pre-eradication mark-recapture monitoring provides data relevant to understanding target species' behaviour and demography and facilitates estimation of detection probability and density. Modern methods of modelling mark-recapture data can also provide knowledge of spatial, temporal, and individual-specific influences on detection probability (White 2005). Such knowledge can provide a critical link between target species' biology and the design and implementation of eradication and post-eradication monitoring. We illustrate this link by describing how kiore (*Rattus exulans* Peale; also called Pacific rat or Polynesian rat) mark-recapture sampling data collected on Aguiguan, Mariana Islands, could be used to inform possible eradication and post-eradication monitoring efforts.

Methods

Kiore history on Aguiguan

Kiore (the only introduced small mammal species known to be present on the island) arrived on Aguiguan, a small (720 ha) island located approximately 8 km southwest of Tinian, Mariana Islands, around 1000 AD (Steadman 1999). We have no information about kiore populations on Aguiguan until the decade prior to World War II, when Japanese administrators developed the island for sugarcane production and instituted

rat-control efforts (Bowers 2001), suggesting high kiore abundance. However, in the decade following the war four scientific expeditions commented on the scarcity of kiore. The first three expeditions found no evidence of kiore, although it is unclear how much effort they expended (Davis 1954). During the three-week period of the fourth expedition, Davis (1954) conducted both visual searches and trapping, using a variety of baits, yet captured zero kiore and observed only two despite high visibility in the relatively open understory browsed by introduced feral goats (*Capra hircus*). In contrast, when scientists next visited Aguiguan in 1983, kiore were frequently observed (Kosaka et al. 1983). Several recent studies provided snap-trap capture rates for kiore, but neither quantified absolute abundance nor obtained genetic samples for species verification (Campbell 1995 [savanna habitat 5.3/100 corrected trap nights (ctn) and limestone forest 10.7/100 ctn]; Cruz et al. 2000 [savanna 9.8/100 ctn, limestone forest 16.5/100 ctn, introduced forest 12.5/100 ctn]; Esselstyn et al. 2003 [limestone forest 1.4/100 trap nights and *Leucaena* forest 8.3/100 trap nights]).

Mark-recapture sampling

Between 22 July and 1 August 2008 (the beginning of the rainy season), we conducted mark-recapture sampling on Aguiguan for 11 consecutive nights on an 11 × 11 grid with 12.5 m intervals between each trap station (nominal grid area = 1.56 ha). This trapping grid was located on the upper plateau near the western end of the island (grid centroid: N latitude 14.854, E longitude 145.552) in an area of forest dominated by native species (e.g. *Guamia mariannae*, *Pisonia grandis*, *Ficus prolixa*). Approximately 15% of the trapping grid (along one edge) consisted of an introduced tree species, *Leucaena leucocephala*. Forested habitat represents the dominant habitat type on Aguiguan (>50%; GHR personal observation); logistical constraints precluded us from sampling other habitats (savanna and a narrow band of coastal strand).

We placed a single standard-length folding Sherman live trap (229 × 89 × 76 mm; H.B. Sherman Traps, Inc., Tallahassee, Florida) at each trap station ($n = 121$). In addition, a single Haguruma wire mesh live trap (approximately 285 × 210 × 140 mm; Standard Trading Co., Honolulu, Hawaii) was placed at every other trap station ($n = 36$); thus Hagurumas were spaced 25 m apart in a regular grid overlaying the Sherman grid. Trap type and spacing were chosen to maximize the likelihood of capturing both kiore and other introduced small mammals present on nearby islands (*Mus musculus*, *Rattus* cf. *diardii*, *R. norvegicus*, *Suncus murinus*; Wiewel et al. 2009) which might be found on Aguiguan. Closed and unbaited traps were placed on the grid one night prior to the beginning of sampling to provide an opportunity for rodents to acclimate to their presence (logistical constraints prevented a longer acclimation period).

We placed traps on the ground and, whenever possible, positioned them to provide shelter from sun and rain. Traps were baited with 1) a mixture of peanut butter, oats, and food-grade paraffin, or 2) coconut meat. We used two bait types to maximize the likelihood of capturing introduced species present in the Mariana Islands (Crabb & Emik 1946). Approximately equal amounts of each bait were offered each night (one bait per trap) in a non-randomized manner.

We checked traps beginning at 0730–0800 each day and closed them during the day to minimize trap mortality. We reopened traps at approximately 1600 and re-baited as necessary

to ensure bait freshness. We used the method described by Nelson & Clark (1973) to account for sprung traps (e.g. from non-target species) when calculating sampling effort.

We examined and measured captured animals to determine species, sex, age, reproductive status, mass (g), head-body length (mm), tail length (mm), right hind foot length (mm), right ear length (mm), and testes length (mm; if applicable). Captured individuals were uniquely marked in each ear with numbered metal ear tags (#1005–1, National Band and Tag Co., Newport, Kentucky). Recaptured animals were examined to determine tag number. We collected genetic material (hair follicles) from all captured rats to confirm species identity. Five randomly-selected samples were analyzed following the mtDNA cytochrome oxidase I procedure outlined in Robins et al. (2007). All capture, handling, and marking techniques followed guidelines approved by the American Society of Mammalogists (Gannon et al. 2007) and the U.S. Geological Survey Animal Care and Use Committee (USGS Fort Collins Science Center).

Abundance estimates were generated in Program MARK 4.3 (White & Burnham 1999) using the conditional likelihood closed capture-recapture model developed by Huggins (1989, 1991). Recapture probabilities were modeled with the same structure as capture probability (i.e. $p = c$) due to sparse data and our primary interest in initial capture probability. We initiated modelling by evaluating six specific time structures to address suspected trap neophobia. Our neophobia models allowed detection probability to vary during the first three (Step3), five (Step5), and seven (Step7) sampling occasions, while holding detection probability constant for remaining sampling occasions. We also allowed neophobia to linearly diminish (i.e. capture probability increased linearly) over the first three (Ramp3), five (Ramp5), and seven (Ramp7) sampling occasions, while holding detection probability constant for remaining sampling occasions. Our motivation for these models came from literature accounts of neophobia for introduced *Rattus* spp. (Temme & Jackson 1979; Inglis et al. 1996; Clapperton 2006), neophobia lasting four days (two days trap exposure plus two days trapping) for *Rattus* cf. *diardii* in the southern Mariana Islands (Wiewel et al. 2009), and from trapping of kiore on Rota (zero captures until two days trap exposure plus three days trapping; Wiewel et al. 2008).

We used the neophobia structure with the greatest support, along with individual and environmental covariates, and behavior (b) to define the global model. Using the global model, we proceeded through a series of more parsimonious models. Covariates under consideration included sex, age (adult or juvenile), body condition, head-body length, body size, and cumulative rainfall (mm) measured at the trap grid center over the prior 24 hour (rain24) or 48 hour (rain48) period. We calculated body condition as the ratio between the observed and expected mass of each individual, where expected mass was determined from a linear regression of ln mass vs. ln length. Body size was a composite variable created from a principal components analysis (Proc FACTOR, SAS Institute, 2003) of mass, head-body length, tail length, hind foot length, and ear length measured for each individual. We evaluated this variable only in the global model in place of head-body length. We used the variable (body size or head-body length) with greatest support to build subsequent models.

Model selection was based on Akaike's Information Criterion corrected for small sample size (AIC_c ; Burnham & Anderson 2002). Models were considered competitive with the top-ranked model when $\Delta AIC_c \leq 2.0$ (Burnham & Anderson

2002). To provide a robust abundance estimate, we model-averaged abundance estimates based on Akaike weights (w_i ; Burnham & Anderson 2002) and included the entire model set except for two models with nonsensical standard errors for β estimates (e.g. $\beta = -11.6$, $SE(\beta) = 42.6$). Burnham & Anderson (2002) recommend the use of summed Akaike weights to evaluate the relative importance of covariates when a balanced model set is used (e.g. in our analysis each variable appeared in 11 models). We also assessed covariate importance by evaluating slope estimates and 95% confidence intervals, where covariates with 95% confidence intervals not overlapping zero were considered influential on detection probability. All estimates are presented as mean \pm 1 SE.

We calculated kiore density by dividing the model-averaged abundance estimate by effective trapping area (ETA), where ETA equaled the total area encompassed by the trapping grid (1.56 ha) plus a boundary strip equal to half the mean maximum distance moved (MMDM) between captures for individuals captured two or more times (Wilson & Anderson 1985).

Results

Captured rats were uniform in morphology and genetic analysis of the mtDNA cytochrome oxidase I gene region of 5 randomly-selected individuals indicated that all were kiore (*R. exulans*; S. J. Oyler-McCance & J. St. John, unpubl. data). We had 62 total captures of 48 kiore (33 females and 15 males), including 14 recaptures of 12 individuals, in 1668 corrected trap nights (1727 total trap nights). Forty-two adults and 4 juveniles were included in mark-recapture analyses after excluding 2 kiore that escaped before being marked. Average mass was 63.3 ± 2.54 g (95% CI = 58.4, 68.3; $n = 46$). Sixty percent (37 of 62) of total captures occurred in Haguruma traps, which made up only 23% (36 of 157) of the traps present on each sampling occasion. No kiore trap mortality occurred and all individuals retained at least 1 ear tag for the duration of the study (2 of 14 recaptured kiore lost one tag). Kiore

were captured with both bait types (37% coconut and 63% peanut butter mixture). No other rodent species were trapped or observed during sampling. Non-target captures consisted of 53 hermit (*Coenobita brevimanus*) and 66 coconut (*Birgus latro*) crabs. Crab bait-specific capture rates were similar to kiore (39% coconut and 61% peanut butter mixture).

Kiore detection probability was low overall and best explained by a model allowing neophobia to diminish linearly (i.e. capture probability increased linearly) until occasion 7 (Ramp7) with additive effects of sex and cumulative rainfall over the prior 48 hours (Table 1). Competitive models mirrored the top model, with the addition of either head-body length, age, or body condition (Table 1). However, covariate importance estimates indicate that head-body length (0.34), age (0.28), and body condition (0.29) are relatively unimportant in comparison to sex (0.70; an importance value ≥ 0.5 indicates that a variable is important to the process being investigated [Barbieri & Berger 2004]). Females were more likely to be captured than males ($\beta = -1.74 \pm 1.03$, 95% CI = $-3.77, 0.30$; Fig. 1). Detection probability increased slightly with increasing rainfall ($\beta = 0.04 \pm 0.02$, 95% CI = $-0.01, 0.08$). For the maximum recorded cumulative rainfall over 48 hours, detection probability doubled (Fig. 2).

Mean maximum distance moved between captures at our forest site was 35.2 ± 5.8 m (95% CI = 23.8, 46.7; $n = 12$). When combined with the nominal grid area of 1.56 ha, this MMDM estimate resulted in an effective trap area of 2.57 ha. Our model-averaged abundance estimate was 141 ± 106 kiore (95% CI = 46, 350), resulting in a density estimate of 55 individuals/ha.

Discussion

What does modelling our kiore mark-recapture data tell us?

Our model-averaged estimate of kiore density in forest on Aguiguan was 55/ha. In comparison, historic nominal density estimates (captures/sampling area) from mark-recapture and

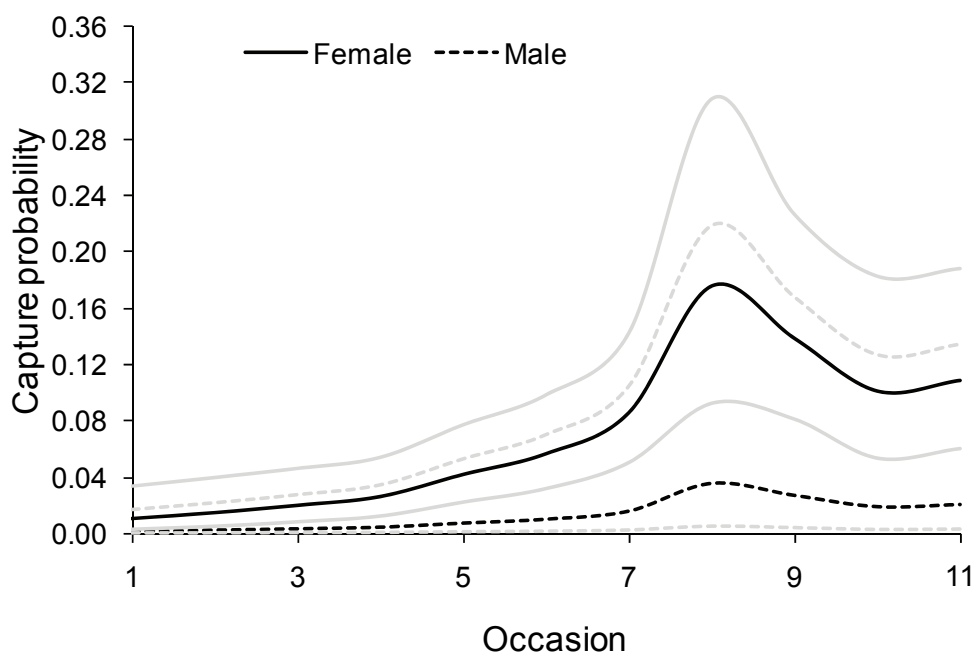


Figure 1. Effect of neophobia (reduced capture probability during occasions 1 through 7) and sex on kiore (*Rattus exulans*) capture probability on Aguiguan, Mariana Islands, 2008. Model also includes the effect of cumulative rainfall over the prior 48 hours, which has a slight positive effect on capture probability. Point estimates are illustrated in black for females (solid line) and males (dashed line) with corresponding 95% lower and upper limits provided in grey.

Table 1. Model selection results for mark-recapture modelling of capture and recapture probability for kiore (*Rattus exulans*) data collected on Aguiquan, Mariana Islands, 2008. Thirty *a priori* models were considered and represent a balanced model set for covariate evaluation. Results include the relative Akaike's Information Criterion corrected for small sample size (ΔAIC_c), Akaike weight (w_i), and number of model parameters (K). See text for abbreviations used in model names.

Model	ΔAIC_c	w_i	K
Ramp7 + sex + rain48	0.00	0.206	4
Ramp7 + sex + head-body length + rain48	1.13	0.117	5
Ramp7 + sex + age + rain48	1.79	0.084	5
Ramp7 + sex + body condition + rain48	1.85	0.082	5
Ramp7 + rain48	2.56	0.057	3
Ramp7 + sex + head-body length + body condition + rain48	2.78	0.051	6
Ramp7	2.98	0.046	2
Ramp7 + sex + age + head-body length + rain48	3.06	0.045	6
Ramp7 + b	3.28	0.040	3
Ramp7 + sex + age + body condition + rain48	3.73	0.032	6
Ramp7 + sex + age + head-body length + body condition + rain48	4.09	0.027	7
Ramp7 + b + rain48	4.21	0.025	4
Ramp7 + body condition + rain48	4.26	0.025	4
Ramp7 + b + sex + age + head-body length + body condition + rain48	4.32	0.024	8
Ramp7 + rain24	4.37	0.023	3
Ramp7 + sex + age + head-body length + body condition	4.49	0.022	6
Ramp7 + age + rain48	4.57	0.021	4
Ramp7 + head-body length + rain48	4.58	0.021	4
Ramp7 + sex + age + head-body length + body condition + rain24	5.91	0.011	7
Ramp7 + head-body length + body condition + rain48	6.30	0.009	5
Ramp7 + age + body condition + rain48	6.30	0.009	5
Ramp7 + age + head-body length + rain48	6.53	0.008	5
Step5	7.39	0.005	2
Ramp7 + age + head-body length + body condition + rain48	8.35	0.003	6
Ramp5	8.39	0.003	2
Step5 + b	9.29	0.002	3
Ramp5 + b	9.83	0.002	3
Step7	10.98	0.001	2
Step3	19.48	0.000	2
Ramp3	19.76	0.000	2

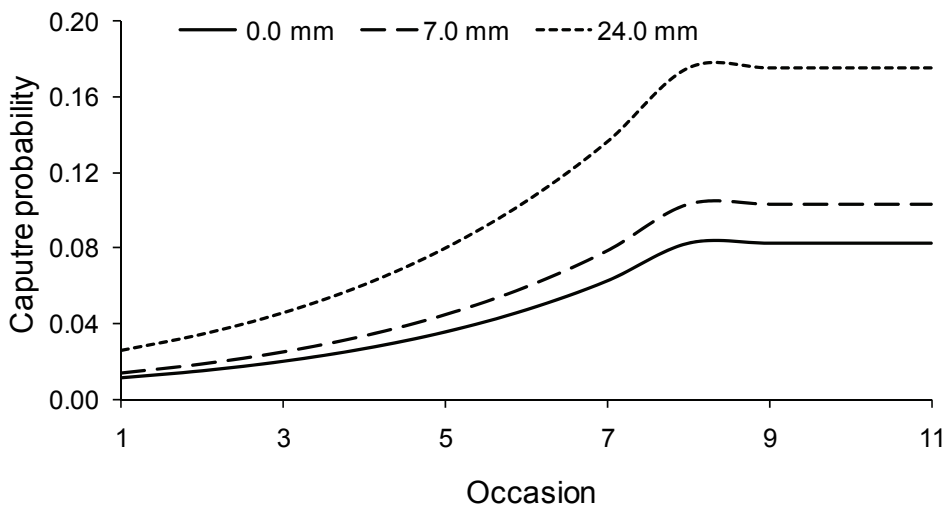


Figure 2. Effect of cumulative rainfall over the prior 48 hours on female kiore (*Rattus exulans*) capture probability on Aguiquan, Mariana Islands, 2008, under three scenarios of no rainfall, average cumulative rainfall (7.0 mm), and maximum cumulative rainfall (24.0 mm) specified for each occasion. A similar additive effect was seen in males but is not illustrated in this figure.

removal sampling in grassland and forest on Guam ranged from 3.1–21.7/ha (Baker 1946; Barbehenn 1969, 1974). More recently, kiore were rarely captured during extensive mark-recapture and removal sampling of grassland, introduced forest, and native forest on Guam, Rota, Saipan, and Tinian (34 captures of 23 individuals in 32,185 total trap nights; Wiewel et al. 2008). Elsewhere in the Pacific, Wirtz (1972) documented kiore densities of 49.4–185.3/ha over 15 months on Kure Atoll and Moller & Craig (1987) found kiore density to range from 6–170/ha in grassland and 10–80/ha in forest over 28 months on Tiritiri Matangi Island, New Zealand. Thus our density estimate (55/ha) would appear to be high for kiore in the Mariana Islands, but in the middle of the range documented elsewhere in the Pacific. Our estimate is consistent with the finding that kiore reach higher densities in isolation from other introduced rodent species (Moller & Craig 1987).

Modelling of mark-recapture data revealed that kiore on Aguiguan had very low detection probability and were highly neophobic compared to *R. cf. diardii* on nearby islands (Wiewel et al. 2009). The duration of this neophobia effect (one day of trap exposure plus seven days of trapping) is without precedent in our studies of introduced small mammals in the southern Mariana Islands (Wiewel et al. 2008, 2009). Although neophobia has been documented for laboratory, commensal, and wild *Rattus* populations (Cowan 1977; Temme & Jackson 1979; Brigham & Sibly 1999; Inglis et al. 1996; Clapperton 2006; Wiewel et al. 2009), available kiore-specific information is equivocal (Clapperton 2006). For example, Harrison & Woodville (1950) documented avoidance of a new food container by kiore in an urban setting, whereas Moors et al. (1992) observed a neophilic response to new objects.

Modelling also indicated that two covariates, sex and amount of rainfall over the prior 48 hours, slightly influenced detection of kiore on Aguiguan. Similarly, sex and daily rainfall amount were important determinants of *R. cf. diardii* detection probability elsewhere in the southern Mariana Islands (Wiewel et al. 2009). For both species, females exhibited higher detection probability than males, and detection probability of both sexes increased with increasing rainfall (Wiewel et al. 2009), suggesting that these factors have general applicability for introduced *Rattus* spp. in the Mariana Islands. Similarly, Davis (1979) noted that female kiore were dominant over males in a captive population. We speculate that the positive relationship between rainfall and detection probability may result from water stress. The limestone substrate of Aguiguan (and throughout the southern Mariana Islands) is highly permeable and available surface water is only temporarily available or nonexistent (Mueller-Dombois & Fosberg 1998), which may lead to increased kiore activity in association with rainfall events.

How can modelling mark-recapture data inform eradication and post-eradication monitoring efforts?

Inferences from our data are necessarily limited by the fact that we were able to sample only one of three habitats on Aguiguan, were not able to gather replicated samples in that habitat, and had relatively low numbers of kiore captures and recaptures (62 captures of 48 individuals). Nonetheless, patterns revealed by modelling of these mark-recapture data are representative of larger phenomena within introduced rodent populations (of varying densities) in the southern Mariana Islands (Wiewel et al. 2008; Wiewel et al. 2009), and perhaps on other tropical islands. Thus, interpretation of our results should not be seen

as prescriptive advice for managers planning introduced rodent eradications, but rather as an illustration of potential insight to be gained by using mark-recapture sampling as one facet of pre-eradication planning.

In a recent review of introduced rodent eradications, Howald et al. (2007) documented a failure rate of ca. 10% (6 of 55) for kiore and suggested several potential explanations for eradication failure, including inadequate bait delivery. Modelling of mark-recapture data, in combination with expected bait consumption rates, can provide a baseline for optimizing toxicant delivery. For example, knowledge of target species density and mean maximum distance moved (ca. 55 kiore/ha and ca. 35 m for kiore on Aguiguan) can assist managers in determining appropriate bait station spacing or aerial toxicant delivery rates.

The strong neophobia we documented for kiore could reduce the effectiveness of bait station-based eradication, but likely only if baiting was of short duration (Nelson et al. 2002). The impact of neophobia on aerial delivery eradication is unclear, although we would expect a lesser impact than for bait stations. Regardless of the toxicant delivery method chosen, managers faced with a potentially neophobic target species should consider planning and budgeting for adequate toxicant delivery rate and duration.

Based on our investigation of covariate importance, sex and rainfall would likely impact the effectiveness of kiore eradication. In a bait station-based eradication we would, on average, expect males to enter bait stations at a lower rate than females. Indeed, the rate of male bait take is likely to dictate the duration of a bait station eradication. The effect, if any, of sex on an aerial delivery eradication is unclear, although dominance of females over males (Davis 1979) suggests that female bait take would exceed that of males. Based on the positive relationship between rainfall and trap capture probability, we might expect increased rainfall to increase the rate of bait take. However, increased rainfall and humidity would likely decrease bait palatability, especially for exposed baits delivered aurally.

The high rate of crab captures (119 captures) during kiore mark-recapture sampling on Aguiguan suggests that non-target bait competition (Rodriguez et al. 2006) or bait station damage could pose a serious impediment to eradication success. Our sampling design which incorporated two bait and two trap types allowed us to better evaluate whether other rodent species were present. We did not find other rodent species during our sampling efforts but prior knowledge of other species can be important in designing eradication efforts (e.g. presence of *Mus musculus* would suggest placing bait stations in closer proximity to one another in order to facilitate mouse eradication; Witmer et al. 2007).

Our modelling efforts illustrate the value of investigating target species' detection probability for post-eradication monitoring efforts. For example, due to the extended neophobia displayed by kiore on Aguiguan (Fig. 3), the short-duration sampling typical of many introduced rodent monitoring programmes (e.g. 3 nights: Witmer et al. 2007; Wegmann et al. 2008) would not have produced the necessary captures to reliably estimate kiore detection probability or density in our study area. In a post-eradication monitoring context, it is unlikely that short-duration sampling would reliably detect the presence of a low-density kiore population exhibiting the level of neophobia observed on Aguiguan. It is possible that an extended trap acclimation period (>1 night) or trap pre-baiting could reduce the neophobia effect, and these possibilities warrant further investigation.

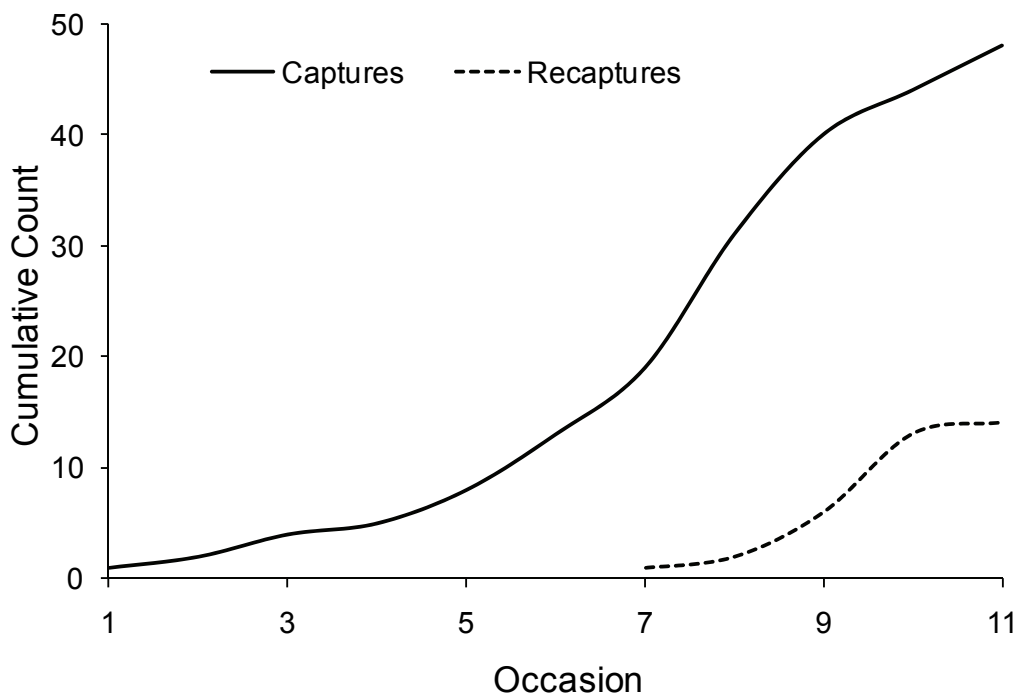


Figure 3. Cumulative kiore (*Rattus exulans*) captures and recaptures over 11 consecutive sampling occasions on Aguiguan, Mariana Islands, 2008. Occasion 1 represents the first night of trapping.

Estimates of detection probability would allow managers to generate various scenarios to help define the duration and timing of post-eradication monitoring (assuming that covariate effects are density independent and that live trapping is employed as the monitoring tool). For example, given a detection probability of 0.08 (at least 8 days of trap experience for females with no rainfall in the preceding 48 hours), 36 trap occasions would be required to ensure a 95% likelihood of capturing any given female during a post-eradication effort (assuming that all females are equally trappable within this population). The post-eradication monitoring effort could be reduced by 58% (to 15 trap occasions) if trapping occurred during periods with 24 mm of rain over the previous two days, suggesting that post-eradication monitoring efforts might be best executed during the rainy season (July through December).

Management of introduced species often requires carefully planned eradication and monitoring efforts. To effectively implement such programmes it is desirable to have baseline data of target species' density and detection probability, as well as knowledge of factors affecting detection. Although rarely quantified, we suggest that these data can greatly assist with the very difficult task of designing efficient and reliable eradication and monitoring programmes. Information about target species' density, detection probability, and factors that influence detection probability could increase the efficiency and reliability of eradication and post-eradication monitoring efforts. Implementation of these data in the planning of toxicant delivery (i.e. delivery method, rate, and duration) not only could increase the likelihood of a successful eradication but also decrease risk of toxicant exposure to non-target species. Similarly, post-eradication monitoring efforts that incorporate information about target species' detection probability increase the likelihood of quickly and correctly documenting the success or failure of eradication.

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