# An Examination of Predator Control Techniques for the Protection of Critically Endangered Species

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A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington
2015

Reading Committee:
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Program Authorized to Offer Degree:
School of Aquatic and Fishery Sciences

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# Abstract

## An Examination of Predator Control Techniques for the Protection of Critically Endangered Species

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Feral cats (*Felis catus*) have been shown to be a main contributor to species decline throughout the world and are especially threatening to insular species that lack adequate defense characteristics. Feral cat control programs have been implemented on islands throughout the world with varied success. Many islands present unique limitations and therefore require custom control strategies. Furthermore, the adaptive nature of feral cat populations makes it difficult to predict space use and the effect of control on population size. To mitigate the impact of feral cats on threatened species, space use data are commonly used to design control strategies. With the use of GPS data logging collars, chapter two describes daily space use and home ranges of feral cats that threaten an endangered species on Rota Island in the Commonwealth of the Northern Mariana Islands. Using 100% Minimum Convex Polygon (MCP), average adult male home range was 1.32 km² and average adult female home range was 0.22 km². Home ranges were deemed fully revealed if asymptotes were reached using incremental analysis. A Michaelis-Menten model was applied to predict home ranges of cats with datasets that did not show convergence. The ability of the model to estimate home ranges of cats with limited location datasets was evaluated by comparing predictions derived from truncations of the full time series of complete datasets. Findings suggest that cat management on Rota should be multifaceted in order to maximize the protection of endangered species and that the Michaelis-Menten model is a useful tool for home range analysis. Chapter three examines the Rota hunting strategy to determine its impacts on the population. A discrete form of the Schaefer model was applied to a 29-month time series of control data. A likelihood framework was used to determine maximum likelihood parameter estimates and calculate population projections to compare control strategies. Model results suggest that the hunting strategy on Rota was effective at initially reducing the cat population, however an unfeasible amount of effort would be required to maintain such a rate of decline. Findings show that it is feasible to maintain cat abundance at lower levels and suggest that a concentrated-effort strategy is preferable to a fixed-effort strategy. While more complex population model forms are available, the Schaefer model is well suited for assessing the impacts of limited predator control programs, such as the one conducted on Rota Island.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ACKNOWLEDGEMENTS

I wish to express sincere gratitude to Dr. James Anderson for his guidance, interest, and willingness to collaborate on this project, and for strengthening my skills in ecological modeling and quantitative research. The second chapter of this research was made possible by Suzanne Medina and the Guam Department of Agriculture's Division of Aquatic and Wildlife Resources. I thank the US Fish and Wildlife Service, Pacific Island Fish and Wildlife Office for funding the feral cat control program and my Master's program, and Reese Brand Phillips for all of his time and guidance. I thank the Commonwealth of the Northern Mariana Islands Department of Land and Natural Resources Division of Fish and Wildlife on Rota. I thank Dr. James Ha and the Ha Animal Behavior Psychology lab for helping review scientific documents and practice presentations. Many thanks to the Anderson and Gallucci labs, including Aneesh Hariharan, Kelsey Vitense, Chloe Bracis, and Jeff Rutter. I am very thankful for all of the field support I received from other biologists on Rota, especially from Sarah Faegre, Phil Hannon, Julia Boland, Kelsey McCune, Lydia Goy, Andria Kroner, Lindsey Nietmann, Jose Antonio Diaz, Kelle Urban, Jen Carpenter, Alex Reyer, Deron Hartman, Brian Holt, and Dane Horowski. Most of all, I thank Dr. Renee Ha for hiring me onto this project and for her continued tenacious persistence in the fight for the conservation of the Mariana crow and the existence of predator research on Rota.

# Chapter 1. INTRODUCTION

## 1.1 BACKGROUND

Introduced predators pose a serious threat to native fauna and are one of the most important causes of declines and extinction of species worldwide (Vitousek et al. 1997, Salo et al. 2007). The introduction of mammalian predators has caused the extinction of many insular species that, having evolved in the absence of predators, lack appropriate anti-predator responses (Blackburn et al. 2004). Feral cats (*Felis catus*) are a primary contributor to the decline of many species and are responsible for the extinction of numerous mammals (Melink 1992, Tershey 2002), reptiles (Iverson 1978, Mitchell 2002), and at least 33 bird species (Lever 1994). Feral cat control programs have been implemented on islands throughout the world with varied success. The plasticity of feral cat populations makes it difficult to predict space use and the effect of control on population growth rate. Furthermore, many islands present unique limitations and therefore require custom control strategies. Research in population and spatial-temporal dynamics is typically needed to design effective and responsible management programs for unstudied feral cat populations. This information is useful for control efforts elsewhere in the world and can provide insight into effective methodologies and removal strategies for other invasive species.

One species threatened by feral cats is the Mariana crow (*Corvus kubaryi*); hereafter crow. The crow is a critically endangered bird found only on the island of Rota, in the Commonwealth of the Northern Mariana Islands. It was extirpated from the neighboring island of Guam by the introduced brown tree snake (*Boiga irregularis*). While there are no brown tree snakes on Rota, the crow population has been in decline since at least 1987 (Plentovich et al. 2005). An island-wide survey on Rota in 1982 suggested a crow population of 1350 individuals (Engbring et al. 1986). By 1995, the population was estimated at 590 individuals, a decline of 56% in 13 years (Fancy et al. 1999). Detections of crows at off-road survey stations declined 83% from 1982 to 1998, a trend that was confirmed by the 67% decline in population estimates using variable circular plot methodology during this same time period (Plentovich et al. 2005). A survey of territorial crow pairs from 1996 to 1999 estimated that only 117 breeding pairs remained on Rota (Plentovich et al. 2005). Point count surveys on Rota showed a 93% decline in the crow population from 1982 to 2004; the largest population decline of all forest birds on Rota during this time (Amar et al. 2008).

Recent field evidence from recovered remains of crows using radio telemetry suggests that feral cats are a contributor to the crow's population decline (S. Faegre and R. Ha, University of Washington, unpublished data). During a home range study from February 2010 through February 2012, 26 crows were fitted with radio transmitters and tracked daily. The mean tracking time for each bird was 256 days. Of the 26 birds, nine of them were found dead and the disposition of the chewed remains provided evidence for feral cat predation. Feral cats could also be a potential threat to nests. Large nestlings have been taken from several nests, suggesting predation either by cats or large monitor lizards. One attempted predation of a large nestling by a feral cat was observed, although the parents successfully drove the cat away before it reached the nest (S. Faegre, comm.). Predation by feral cats has also been proposed as a cause for the widespread declines of other bird species on Rota (Amar et al. 2008).

Picture 1. Mariana crow fitted with radio transmitter.

Feral cat control strategies often include techniques such as leg hold and live box trapping, hunting, poisoning, introduction of disease, and fertility control (Nogales 2004, Robertson 2008). Removal is often effective when multiple techniques are combined; however, technique selection can be constrained by island properties such as accessibility, topography, politics, ethics, and presence of endangered or sensitive species. Feral cat removal methods on Rota are limited in part because of the presence of the critically endangered crow. The crow is an omnivore and also scavenges. This precludes the use of poison as a predator control option because of the risk of secondary poisoning of the crow. Additionally, introducing a feline viral disease is controversial for ethical reasons and because many of the 2000 island residents own cats. This leaves two viable control options on Rota: spotlight hunting and live box trapping. Since managers on Rota are limited to only two removal techniques, it would be beneficial to improve each technique. The primary objective of this thesis is to uncover information that can be used to improve both control techniques. In the second chapter we discuss feral cat space use on Rota, and provide information that managers can use to target cats. In the third chapter, we use a mathematical model to determine the effect of spotlight hunting on the feral cat population. The model provides information that can be used to improve the efficiency of the hunting technique, thereby maximizing the protection of the critically endangered Mariana crow.

## 1.2 STUDY AREA

Rota (14º10'N, 145º12'E) is a part of the Commonwealth of the Northern Mariana Islands, USA and is the second southernmost island of the Marianas Archipelago, a chain of 15 small islands located approximately 1500 km east of the Philippine Islands. Rota is 18 km long and 4.8 km wide. The climate is tropical with an average annual temperature of 26°C (Amar et al. 2008). Precipitation is seasonal with a rainy season from July to October, and averages 2,000 - 2,500 mm (Mueller-Dombois and Fosberg 1998). Approximately 60% of the island is covered in native limestone forest (Falanruw et al. 1989), with undisturbed areas surrounding the base of a limestone mesa known as the Sabana, and on precipitous coastal shelves (Fancy et al. 1999). Feral cats have been observed throughout most of the island (B. T. Leo, University of Washington, unpublished data). Additionally, domesticated cats supported by the 2000 human inhabitants likely contribute to the feral population.

# Chapter 2. HOME RANGE ESTIMATES

## 2.1 INTRODUCTION

Introduced predators pose a serious threat to native insular species that lack adequate predator defense characteristics (Blackburn et al. 2004) and are one of the most important causes of declines and extinction of island species worldwide (Vitousek et al. 1997, Salo et al. 2007). Feral cats in particular are one of the most widespread alien predators on islands (Medina et al. 2011). Because of their plasticity and generalist diet, feral cats thrive in sub-Antarctic, temperate, desert, and tropical ecosystems (Van Aarde 1983, Burrows et al. 2003, Rodríguez et al. 2006, Harper 2007). They are primary contributors to the decline of many species and are responsible for the extinction of numerous mammals (Melink 1992, Tershey 2002), reptiles (Iverson 1978, Mitchell 2002), and at least 33 bird species (Danner et al. 2010). Of special concern is the Mariana Crow, that was extirpated from Guam by the introduced brown tree snake (Plentovich et al. 2005) and is now critically impacted by cats in its only remaining habitat, Rota, a neighboring island to Guam in the Commonwealth of the Northern Mariana Islands, USA (S. Faegre and R. Ha, University of Washington, unpublished data).

To develop appropriate management strategies for feral cats in general and for Rota Island specifically, it is necessary to understand feral cat behavior and the characteristics of the population. Previous research shows that movement patterns and habitat use vary widely with geographic location and climate. Home range estimates vary from 3.65 km$^2$ ($n$ = 22) to 22.11 km$^2$ ($n$ = 19) in woodland habitat for both males and females (Edwards et al. 2001, Molsher et al. 2005). This variability poses a difficulty when applying previously reported feral cat home range results to unstudied populations.

A feral cat control program has been in operation on Rota since February 2012; however, the dynamics of the Rota population are largely unknown. From 2012 to 2014, the control program used two removal techniques: hunting with spotlights and live box trapping, with other trapping methods incorporated in 2015. The use of poison and disease are precluded due to risk of secondary crow poisoning and infection of pet cats. Hunting is done throughout the island on all public roads near crow territories. On-foot hunting is problematic because of dense jungle vegetation. Trapping is conducted in crow territories that are further away from roads. Currently it is unclear how much effort should be apportioned to each technique, and to what degree of intensity each technique should be applied in distinct locations.

In general, feral cat space use data are useful for managers in a number of ways. Early results from the removal program show that hunting returns a higher catch per unit effort (CPUE) than trapping (B. T. Leo, University of Washington, unpublished data). However, hunting is conducted from vehicles and therefore might have limited protective value because many crows occupy habitat that is inaccessible by roads. If feral cat home ranges were large, hunting would be justified because cats near roads might also venture into distant crow territories. Conversely, if cat home ranges were small, targeted trapping near known crow locations would be a more effective way to protect the crow. Home range and daily space use information would also contribute to strategic trap placement and spacing. This information is useful for control efforts throughout the world and can provide insight into effective methodologies and removal strategies for feral cats and other invasive species.

Location data are commonly analyzed using incremental area analysis to determine if home ranges are fully revealed. While this technique is logically sound, currently there is no standard way to quantitatively describe the results. Additionally, GPS logging devices sometimes collect fewer data than intended. It would be useful in these cases to apply models to the data, so that additional information might be extracted. Here, we introduce methods to quantitatively describe incremental area analyses and extract information from datasets with fewer locations.

This chapter has three primary objectives: 1) to obtain preliminary home range estimates of feral cats on Rota Island and describe space-use behavior in order to inform management decisions, 2) describe a quantitative methodology to objectively determine home range revelation, and to predict home range given datasets with fewer locations, and 3) inform future projects by determining the amount of time and data needed to adequately reveal home ranges.

## 2.2 CAPTURE AND RECOVERY PROTOCOLS

The field work for this chapter was conducted from June through August 2014. To minimize threats to crows, all home range work was conducted in areas that had little or no observed crow activity. This constraint prevented the exploration of the relationship between cat movement and crow territories. All procedures were approved by the University of Washington Animal Care and Use Committee (#2858-04).

Tomahawk™ (Tomahawk Live Trap Company, Tomahawk, WI) live box traps (81 x 25 x 30 cm and 66 x 23 x 23 cm) were baited with canned fish, set in the afternoon, and checked in the morning. Upon capture, cats were anesthetized via intramuscular injection of Ketamine (10 mg per kg) and Mydazolam (.4 mg per kg). Cats were only collared if collar weight (65 g) was below 5% of the cat's body weight. Collars were equipped with Very High Frequency (VHF) transmitters that emitted signals during day and nighttime hours. To recover collars, cats were radio-tracked and shot. Once collars were recovered, they were re-programmed and deployed on additional cats.

## 2.3 COLLAR PROGRAMMING

Four GPS data logging collars were used (Advanced Telemetry Solutions (ATS) GPS Logger model W500, G2110G). Collar programming was done with the use of ATS programming software (ATSfixes for Loggers version 4.2W). Because cat activity has been shown to vary inversely with ambient temperature in equatorial regions (Konecny 1987), collars were programmed to attempt GPS fixes during nighttime and crepuscular hours to maximize fix attempts during peak cat activity hours.

Collar program schedules were modeled after another feral cat GPS collar study (Recio et al. 2010). Initially collars were programmed to attempt 32 GPS fixes per day, with an attempt every half hour from 1800 to 0700, and an attempt every other hour from 0700 to 1700. Maximum time for a fix attempt was 180 seconds. Unsuccessful fixes were recorded and a new fix was attempted in the next scheduled interval. This schedule was applied to the first four cats, however one of the collars malfunctioned and was therefore not recovered. The other three collars were successfully recovered and redeployed on new cats. The frequencies of the last two fix schedules were increased due to time constraints (Table 2.1).

Time of fix was recorded for all successful fixes. Using ArcMap 10.1, daily polygons (midnight to midnight) were calculated using 100% Minimum Convex Polygon (MCP) (Kenward 2001) for each cat. For the first six cats, inaccurate fixes were eliminated by rejecting fix positions with Horizontal Dilution of Precision (HDOP) values > 4 (Recio et al. 2011). Because the seventh cat had a shorter deployment period and therefore smaller dataset, the rejection criterion was increased to HDOP values > 6.

Table 2.1. Fix Schedules for all collars

| Cat | Capture date | Sex | Fixes per day | Tracking period (days) |
|---|---|---|---|---|
| M1 | 7 Jul 2014 | M | 32 | 42 |
| F1 | 10 Jul 2014 | F | 32 | 46 |
| M2 | 13 Jul 2014 | M | 32 | 46 |
| F2[1] | 18 Jul 2014 | F | 32 | |
| F3 | 25 Aug 2014 | F | 32 | 14 |
| M3[2] | 26 Aug 2014 | M | 36 | 14 |
| F4 | 3 Sep 2014 | F | 50 | 8 |

## 2.4 HOME RANGE CALCULATION AND PREDICTION MODELS

All home ranges were calculated using 100% MCP. Horizontal Dilution of Precision values were used in the same fashion as above. Incremental area analyses (Kenward 2001) were conducted for each dataset using the model builder feature in ArcMap 10.1. R software was used to analyze each dataset to determine if asymptotes were reached (R Core Team 2014). The pattern of increasing area with time was characterized with a Michaelis-Menten (MM) model (eq. 2.1) (Michaelis and Menten 1913),

$$Area = \frac{Amax * t}{K + t} \tag{2.1}$$

where *Area* is area calculated using 100% MCP, *Amax* is an empirically derived estimate of the asymptote (home range), the Michaelis constant *K* is the number of days at which *Area* is half of *Amax*, and *t* is time of location fix. Coefficients were estimated with the *nls* nonlinear regression function in R.

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[1] No data were collected for this cat because of a collar malfunction.

[2] Juvenile male.

## 2.5 RESULTS

### 2.5.1 *Daily Space Use*

Two adult males, three adult females, and one juvenile male were successfully captured and collared (Figure 2.1).

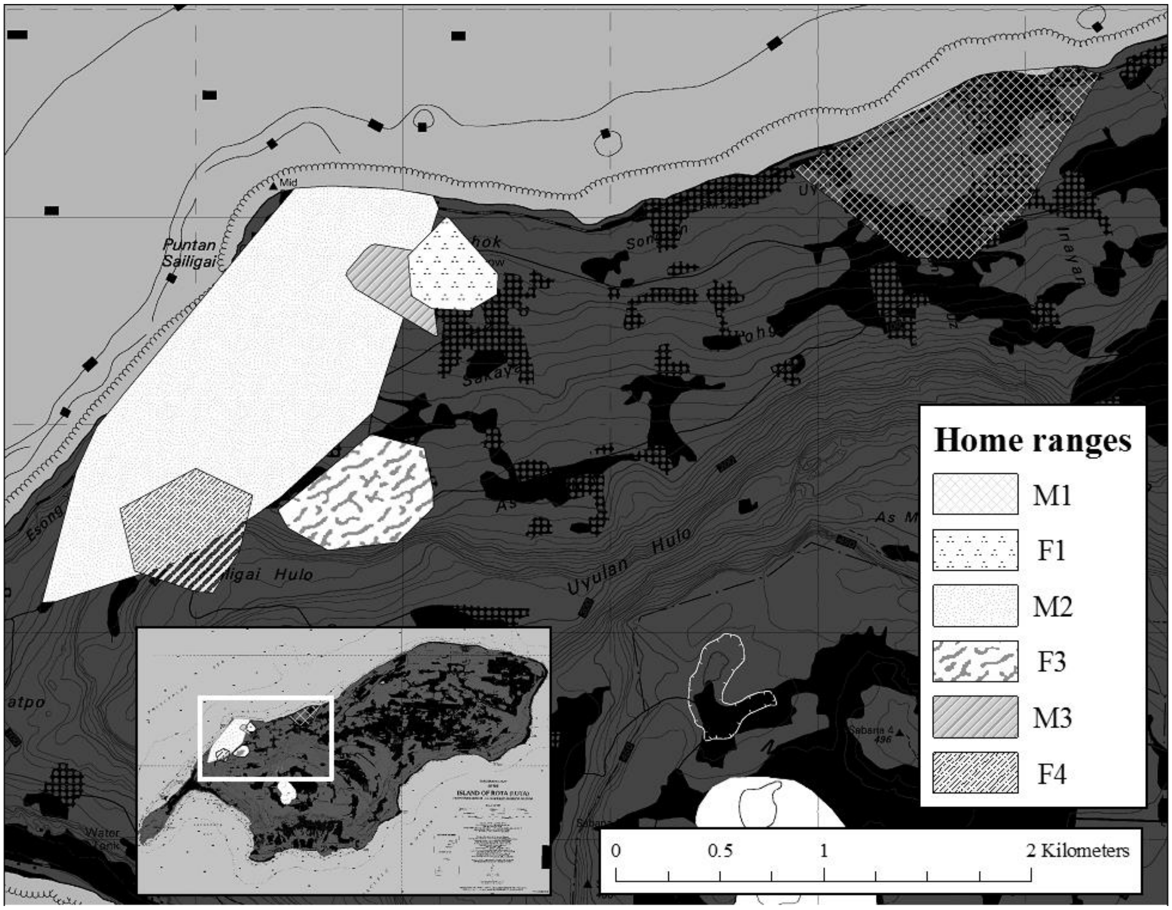

Figure 2.1. Home range estimates using 100 % Minimum Convex Polygons (MCP) for feral cats on Rota Island.

On average both adult males used a similar amount of area per day despite having considerably different overall home range sizes, indicating that daily space use is independent of home range size (Table 2.2)

Adult males were capable of traveling relatively long distances in short periods of time, with a maximum distance of 2.4 km traveled within one day. Adult males used more area per day than females. Mean percent home range use per day and mean total area use per day were smaller for F1 than for other females. Cats tended to have a near normal distribution with a right skew for percent home range use per day and total area use per day.

Table 2.2. Daily space use statistics for feral cats on Rota Island, Commonwealth of the Northern Mariana Islands, USA from June - September 2014.

| | | Percent home range use per day | | | | $\text{km}^2$ per day | | | |
|---|---|---|---|---|---|---|---|---|---|
| Cat | *n* | $\bar{x}$ | SD | *range* | | $\bar{x}$ | SD | *range* | |
| M1 | 42 | 38.5 | 11.7 | 13.2 | 67.1 | 0.29 | 0.09 | 0.01 | 0.51 |
| F1 | 46 | 16.1 | 9.2 | 4.3 | 44.7 | 0.02 | 0.01 | 0.01 | 0.06 |
| M2 | 46 | 38.9 | 11.9 | 17.0 | 64.2 | 0.73 | 0.22 | 0.32 | 1.2 |
| F3 | 14 | 28.6 | 11.8 | 9.3 | 46.1 | 0.09 | 0.04 | 0.03 | 0.14 |
| F4 | 8 | 26.6 | 8.5 | 10.4 | 36 | 0.07 | 0.02 | 0.03 | 0.1 |
| M3 | 14 | 19.2 | 12.9 | 4.3 | 46.6 | 0.02 | 0.01 | 0 | 0.05 |

### 2.5.2 *Home Range*

The three cats tracked for >40 days all reached asymptotes while the three cats tracked for shorter periods showed less evidence of reaching asymptotes (Figure 2.2).

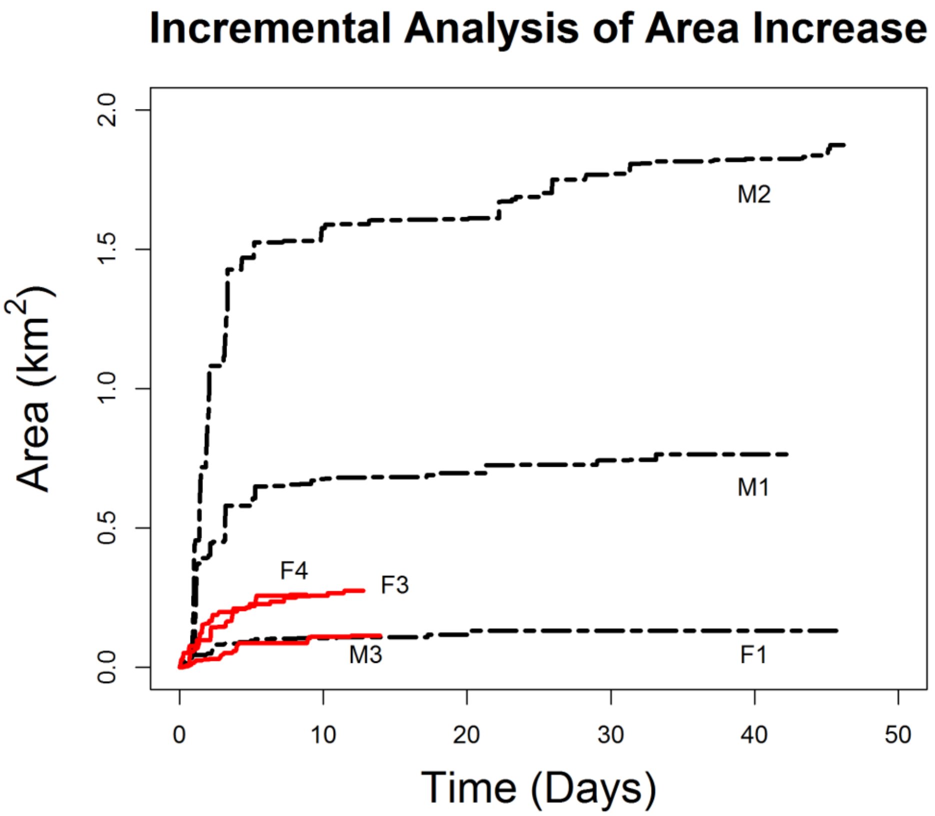

Figure 2.2. Incremental area analysis for all six cats. Dashed lines indicate cats that show more evidence of reaching asymptotes.

We base this judgment on the small error between *Amax* and MCP for the cats tracked for >40 days and the large difference for cats tracked for shorter periods (Figure 2.3, Table 2.3). Inspection of the progression of the *Amax* estimate through time for the >40 day datasets showed that *Amax* estimates did not appreciably differ from the final *Amax* estimate after day 14 (Figure 2.4). The analysis showed that the MM model accurately estimated home range in a relatively short amount of time and with relatively few locations. For M1, *Amax* was estimated within a 2%

margin of error after 14.2 days and 388 locations. Similarly for M2, *Amax* was estimated within a 3.6% margin of error after 14.1 days and 303 locations.

All three >40 day progressions showed similar behavior: an over estimate followed by a convergence to the final *Amax* estimate (Figure 2.4). The progression of the *Amax* estimate for the limited datasets showed similar behavior with less evidence of convergence. We draw conclusions on home range size for the more limited datasets based on the pattern of *Amax* estimates through time from the larger datasets of M1 and M2, where *Amax* converged to a fixed value with increasing time of observation.

The MM model estimates of *Amax* for the limited datasets also suggested convergence.

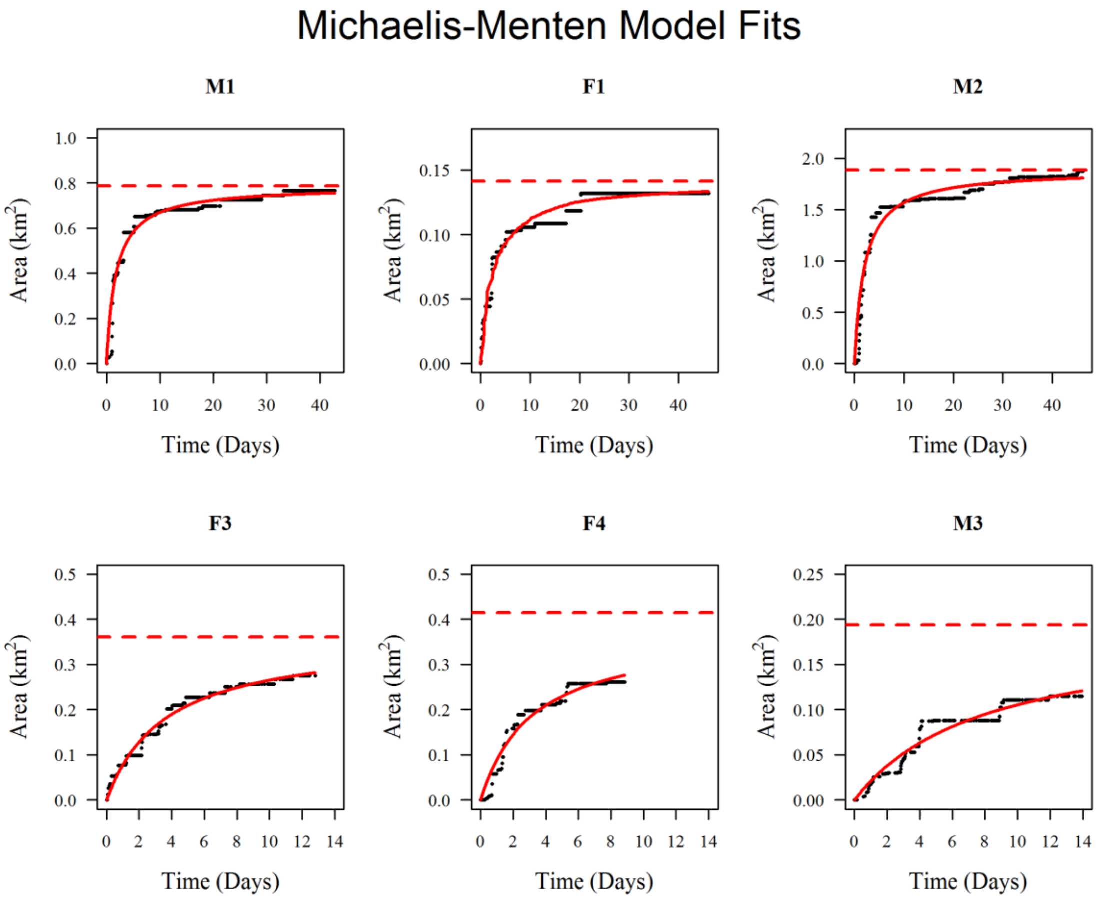

Figure 2.3. Application of the Michaelis-Menten model to home range data. Dashed lines indicate Amax estimates when the model is applied to the entire dataset. Red solid lines indicate the model fit to the data. Black dots indicate area calculated using 100% MCP.

Since F3 and M3 datasets approached 14 days, which in the case of M1 and M2 gave *Amax* within 3.6% of the final *Amax*, we suggest *Amax* for F3 and M3 are resolved to the same level of uncertainty (Table 2.3). The F4 cat was tracked for fewer days and therefore fewer locations were recovered. The progression of the F4 *Amax* through time nonetheless showed a similar pattern; although less pronounced and still on a downward trend before terminating at the final *Amax*. We suggest that the true home range for F4 is slightly lower than estimated by the MM model.

Table 2.3. Home range estimates (km²) of feral cats on Rota Island, Commonwealth of the Northern Mariana Islands, USA using 100% Minimum Convex Polygon and the Michaelis-Menten model.

| Cat | MCP | *Amax* | *Amax* - MCP | % dif[3] | Successful fixes |
|---|---|---|---|---|---|
| M1 | 0.77 | 0.78 | 0.01 | 1.7 | 1229 |
| F1 | 0.13 | 0.14 | 0.01 | 6.1 | 1224 |
| M2 | 1.87 | 1.89 | 0.01 | 0.6 | 954 |
| F3 | 0.28 | 0.36 | 0.09 | 30.9 | 309 |
| M3 | 0.11 | 0.19 | 0.08 | 65.8 | 336 |
| F4 | 0.26 | 0.38 | 0.11 | 43.8 | 268 |

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[3] Percent difference is the percentage of the MCP estimate that is the difference in *Amax* and MCP.

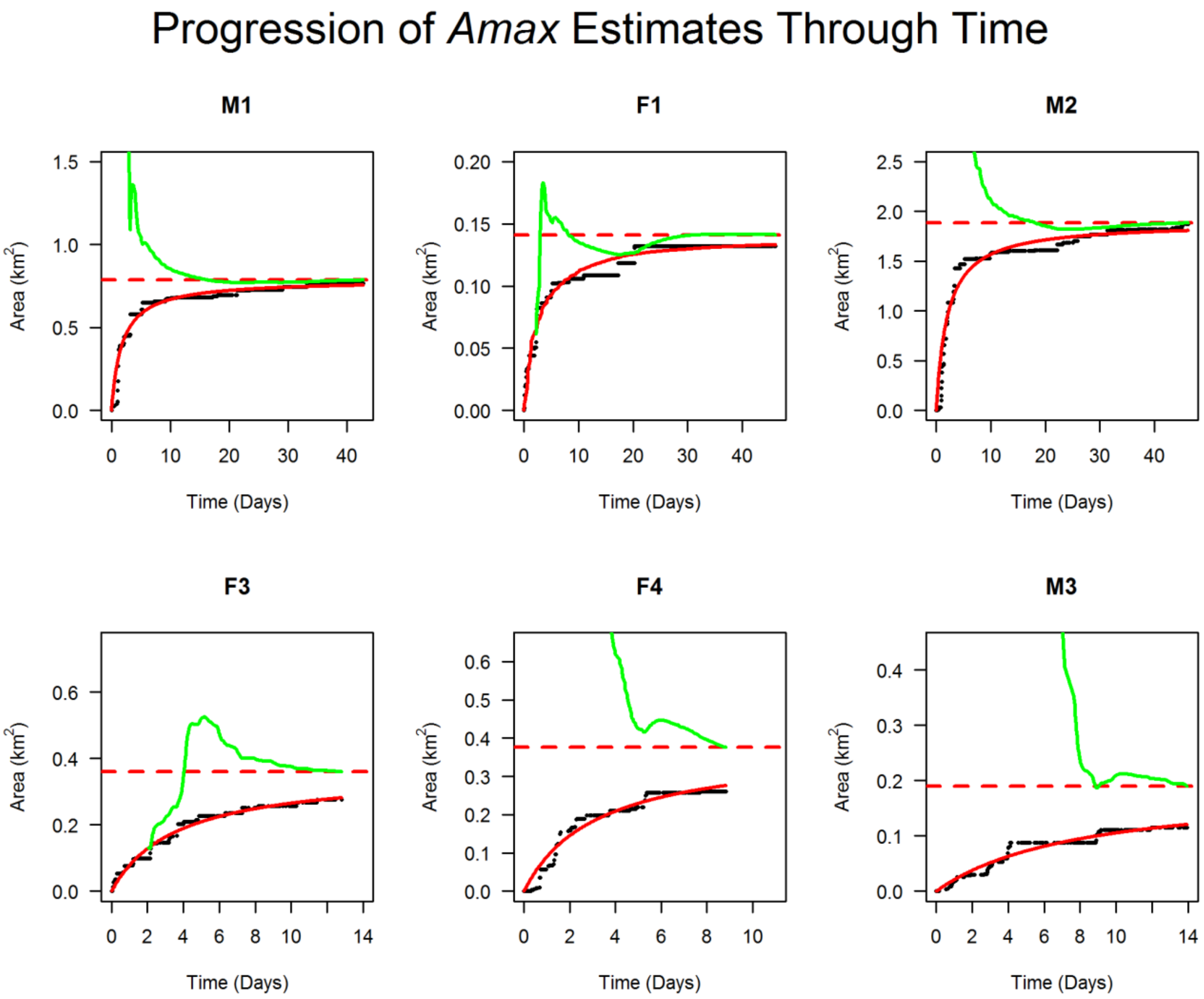

Figure 2.4. Progression of *Amax* estimates through time for all six datasets. Green line indicates *Amax* estimate for all data up to time (*t*).

## 2.6 DISCUSSION

### 2.6.1 *Daily Space Use*

Daily space use analyses showed that male cats are capable of traveling relatively long distances in short periods of time. With an increase in area use, additional effort is needed to maintain the effectiveness of the trapping removal method. This is especially true on Rota because of the inherent difficulty of transporting traps in thick jungle and uneven terrain. The hunting removal strategy should be the most effective removal strategy against males because it likely results in a higher CPUE for cats with large home range size. Female cats generally used small amounts of area per day. These findings support a management strategy that focuses on targeted trapping as opposed to hunting, which would be ineffective if the cats used areas away from roads.

### 2.6.2 *Home Range Size*

Feral cat home ranges on Rota appear to be relatively small; average male and female home ranges were lower than 8 other studies in Pacific regions (Jones and Coman 1982, Fitzgerald and Karl 1986, Konecny 1987, Norbury et al. 1998, Smuker et al. 2000, Edwards et al. 2001, Molsher et al. 2005, Goltz et al. 2008). The abundance of rat and mice species on Rota may account for the reduced home ranges (Wiewel et al. 2009). Spatial behavior has been associated with resource distribution and is a function of social system and sex (Schoener 1981, Pierce et al. 2000, Boydston et al. 2003, Mitchell and Powell 2004, Ross et al. 2012). Carnivores in general expand their home range size when prey abundance is scarce (Litvaitis et al. 1986, Powell et al. 1997, Herfindal et al. 2005, Ross et al. 2012). On Rota, rodent abundance is high and stomach content analysis from cats removed via hunting showed that rodents make up the majority (82%) of cat diet (B. T. Leo, University of Washington, unpublished data). Skinks and geckos are also abundant (Fritts et al. 1990) and make up much of the remaining portion of the diet of adult cats.

Because mesocarnivores are often preyed on by larger sympatric members of their guild, cover is an important habitat feature influencing home range size (Donadio and Buskirk 2006, Hunter and Caro 2008, Ross et al. 2012). However, feral cats have no predators on Rota and thus may not be heavily influenced by cover availability. Therefore, abundant food resources are likely to be the determining factor for small home ranges on Rota.

### 2.6.3 *Human Influence on Feral Cat Space Use*

Humans can also influence home range through their impacts on food availability and prey densities. The home range of M1 overlapped with human picnic areas and was half that of M2 which was distant to human picnic activity. By similar reasoning, the small home range of F1 could be attributed to its location in the island dump, which presumably attracts rats because of the steady influx of human waste and food. This is supported because the F1 home range was half that of the other females that occupied areas away from human influence. Finally, the limited home range of M3 can be attributed to its juvenile status.

#### 2.6.4 *Michaelis-Menten Model*

Results indicate that the tracking period for cats on Rota should be set at a minimum of two weeks with a minimum fix schedule of 32 fixes per 24-hour period in order to fully reveal home ranges. These findings are similar to another feral cat study that reported tracking periods from 3 to 18 days and suggested a minimum number of 460 locations (Recio et al. 2010).

This chapter demonstrates that the MM model gives insight into location data in a number of ways. It provides a quantitative means to determine if home ranges are fully revealed through the comparison of *Amax* and MCP. It allows for the quantitative description of incremental data, which facilitates transparency and reduces subjective interpretation. The analysis of the progression of *Amax* through time can reveal the minimum amount of time or number of locations necessary to obtain reliable home range estimates; this information is useful for planning efficient home range studies. Lastly, if home ranges are only partially revealed, then the model provides a viable approach to home range prediction. Previous feral cat home range studies (Recio et al. 2010, Martin et al. 2013) estimated home ranges by visual inspection of data and found that some data did not show convergence. Therefore, in those cases home ranges were likely underestimated. Applied to such data, the MM model gives valuable insight by quantitatively predicting home range size. However, predictions should be made with care as the model can only reveal patterns that can vary among individuals. It would be informative to apply the MM model to the unrevealed home range data.

### 2.7 CONCLUSION

The hunting removal technique may be most effective for removing male cats given their large home ranges and low trap encounter probabilities. However, this technique is unlikely to be effective at removing cats that have small home ranges located in areas that are inaccessible by roads. With the use of trail cameras or other cat identification technology, a targeted trapping approach is likely to be more useful for eliminating such cats. The integration of these two techniques may be the best way to maximize the protection of the crow. We suggest that managers implement both hunting and trapping techniques since they both have unique protective value to the crow. While more samples increase confidence of home range estimates, the MM model proves a useful analytical tool for home range inference and allows for the extraction of information from limited datasets. It also shows that cat home ranges can be revealed in relatively short time periods on Rota. The MM model can likely be applied to other species in this context.

# Chapter 3. POPULATION MODEL

## 3.1 INTRODUCTION

Feral cats have been introduced by humans to most parts of the world including at least 65 major island groups and many remote oceanic islands, both inhabited and uninhabited (Courchamp 1999). In closed insular ecosystems, introduced cats are known to be the direct cause of severe reduction or extinction of numerous populations of local vertebrate species (Iverson 1978, Taylor 1979, Moors and Atkinson 1984, King 1985, Courchamp 1999). The Mariana Crow was extirpated from Guam by the introduced brown tree snake (Plentovich et al. 2005) and is now critically impacted by cats in its only remaining habitat, Rota, a neighboring island to Guam in the Commonwealth of the Northern Mariana Islands, USA (S. Faegre and R. Ha, University of Washington, unpublished data).

Feral cat control strategies often include techniques such as leg hold and live box trapping, hunting, poisoning, introduction of disease, and fertility control (Nogales 2004, Robertson 2008). In insular ecosystems, the applications of such strategies are often dictated by factors such as island size, climate, sensitivity of non-target species, or human inhabitation. Feral cat removal methods on Rota are limited in part because of the presence of the critically endangered crow. The crow is an omnivore and also scavenges. The risk of secondary poisoning of crows via scavenged rat carcasses precludes the use of poison as a control agent. Additionally, the introduction of a feline viral disease is controversial because many of the island residents own pet cats. Live trapping has proven to be difficult on Rota because of interference from multiple non target species including rats, mice, coconut crab, chickens, and monitor lizards. Models have shown that Trap-Neuter-Release (TNR) removal strategies are successful at decreasing feral cat populations if >57% of cats are captured and neutered annually (McCarthy 2013). The same study showed that Trap-Vasectomy-Hysterectomy-Release (TVHR) caused population decline with an annual capture rate of ≥ 35%. Capture rates such as these would be very difficult to achieve on Rota. Therefore, two main control strategies have been employed: spotlight hunting and live box trapping.

Since managers on Rota are limited to only two removal techniques, it is important to fully understand how each affects the cat population, and how much protective benefit each has for the crow. Here, we determine the effect of the spotlight removal technique on the feral cat population with the use of a Schaefer model during a two-year time period. We also conduct a cost-benefit analysis to identify a strategy that maximizes efficiency. We conclude that spotlight removal is capable of reducing the population initially but requires significant effort to sustain the rate of population decline, and that the strategy that maximizes efficiency involves periods of intense effort followed by periods of lower effort as opposed to constant levels of effort. Spotlight hunting is a good technique for short term feral cat population reduction, however other strategies are needed to significantly reduce the population and to maximize crow protection.

### 3.1.1 *Hunting*

The data used in this study were collected from late February 2012 to June 2014; however, no hunting was conducted during July 2012 and April 2014 due to permitting and logistic issues (Figure 3.1). Hunting occurred at night from a vehicle on all public roads that were at least 200m away from domiciles (Figure 3.2). Spotlights were used to illuminate cat habitat; once cats were identified they were pursued and shot with either a 10/22 Ruger rifle or 410 Mossburg shotgun. Removal locations were recorded using Garmin GPSMAP 60CSx handheld GPS Navigator units. Other data collected included time of removal, pelage, sex, age (kitten/adult), locations, time of locations, and pelages of cats that were observed and not shot.

There were multiple cat control technicians employed throughout the project. The field project manager started the program in February 2012 and was the exclusive hunter until July 2013. From August 2013 to June 2014, three removal technicians were employed.

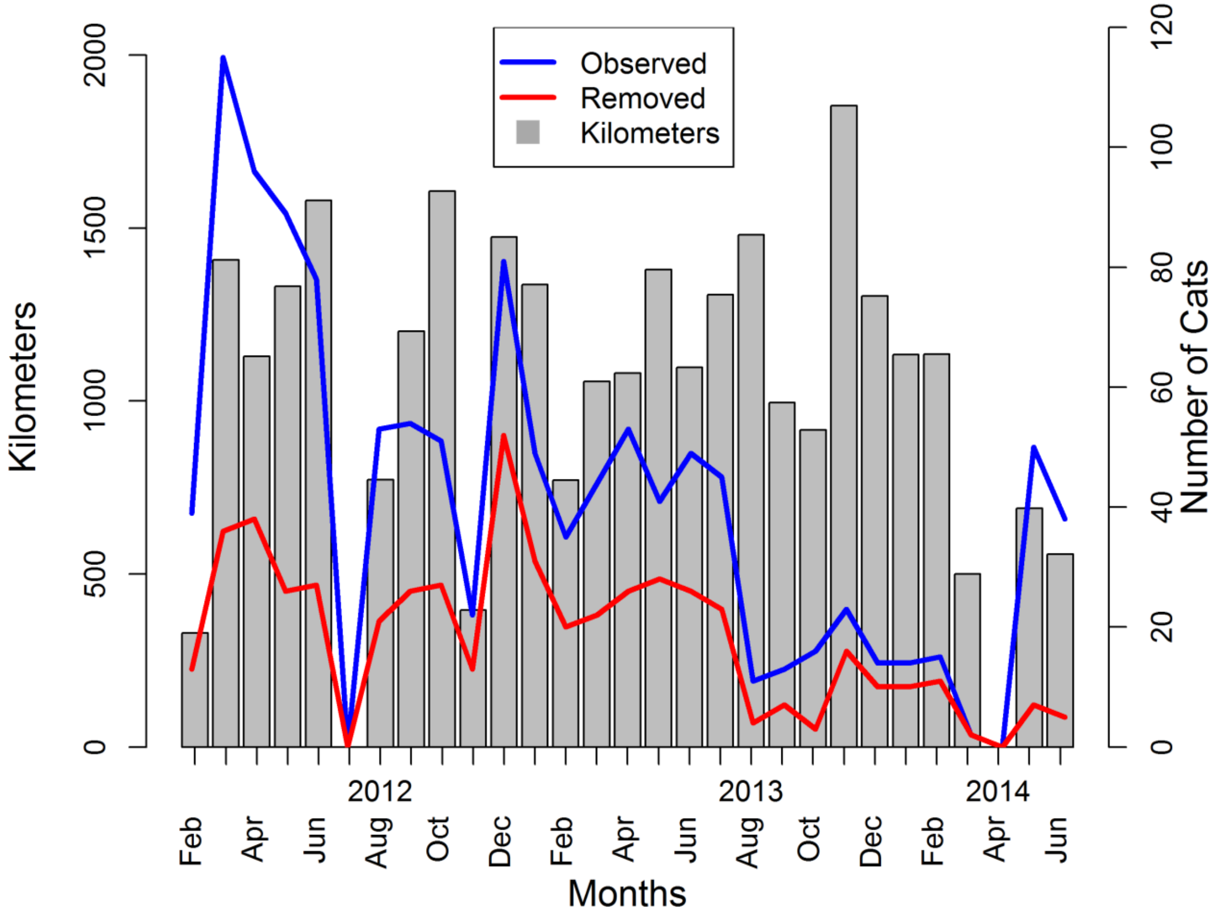

Figure 3.1. Number of cats that were observed (blue line) and removed (red line) for each month during the removal program. Grey bars indicate number of kilometers driven in each month.

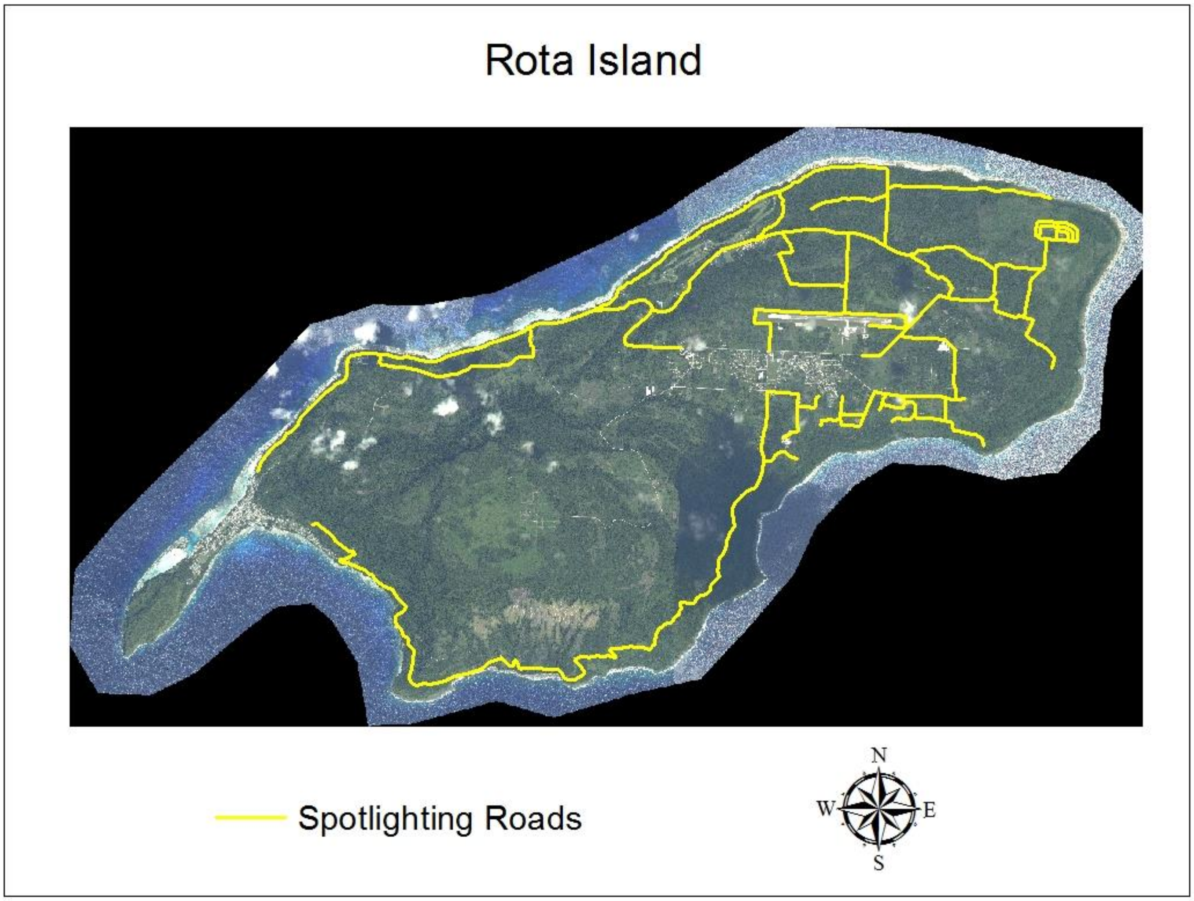

Figure 3.2. Spotlight Roads on Rota Island.

### 3.1.2 *Population Model*

Our model is designed using methodology outlined in Hilborn and Mangel 1997. We characterized the feral cat population on Rota using a discrete form of the Schaefer model: (eq. 3.1):

$$N_{t+1} = N_t + rN_t\left(1 - \frac{N_t}{K}\right) - R_t \tag{3.1}$$

Where *N* is the estimated population at time *t*, *r* is the maximum possible population growth rate, *K* is the carrying capacity, and *R* is the number of cats removed at time *t*. We use monthly increments of time. The model was run using R version 3.1.2 (R Core Team 2014). Data from spotlight surveys were used to calculate observed values of *N* (eq. 3.2):

$$N_{obs,t} = \frac{I_t}{q} \tag{3.2}$$

Where *q* is a catchability coefficient and $I_t$ is cats removed per mile driven for each month, or Catch Per Unit Effort (CPUE). We assume that $N_{obs,\,t}$ are related to true population size with lognormal distributed observation uncertainty ($V_t$.) (eq. 3.3):

$$N_{obs,t} = N_t V_t \tag{3.3}$$

Hilborn and Mangel 1997 show that the deviation between the observed and true values of the logarithm of population size is normally distributed with mean 0 and variance $\sigma_v^2$, so that the likelihood of a deviation size $d_t$ is (eq. 3.4):

$$Likelihood = \frac{1}{\sqrt{2\pi\sigma_v^2}}\exp\left(-\frac{d_t^2}{2\sigma_v^2}\right) \tag{3.4}$$

And the negative log-likelihood (*L*) for the observation at time *t* is (eq. 3.5):

$$\mathrm{L}_t = \log(\sigma_v) + \frac{1}{2}\log(2\pi) + \frac{d_t^2}{2\sigma_v^2} \tag{3.5}$$

Estimates for *r* and initial population size, $N_0$, were calculated independently from the population model with standard deviations $\sigma_r$ and $\sigma_{N_0}$. Negative log-likelihoods were calculated for both estimates, assuming normal distributions for both parameters. The negative log-likelihood for all of the data is the sum (across all observation periods) of the $L_t$ from equation (3.5), and the negative log-likelihoods of $r$ and $N_0$, giving a total negative log-likelihood of

$$L_{total} = \left[ \sum_{t=0}^{n} \log(\sigma_v) + \frac{1}{2}\log(2\pi) + \frac{d_t^2}{2\sigma_v^2} \right] + \left[ \log(\sigma_r) + \frac{1}{2}\log(2\pi) + \frac{(\hat{r}-r)^2}{2\sigma_r^2} \right] + \left[ \log(\sigma_{N_0}) + \frac{1}{2}\log(2\pi) + \frac{(\hat{N}_0 - N_0)^2}{2\sigma_{N_0}^2} \right] \quad (3.6)$$

where $\hat{r}$ is observed maximum possible population growth rate and $r$ is true maximum possible population growth rate, $\widehat{N}_0$ is observed initial population, and $N_0$ is true initial population. Given the data and particular values of $q$, $r$, $K$, $N_0$, and $\sigma_v^2$ , the likelihood of that set of parameters was evaluated. Here we select the parameters that make the negative log-likelihood as small as possible and call these "best-fit" parameters. This was done using the *optim* function in R. The best-fit parameters were then used to make predictions of the effects of spotlight hunting on cat abundance.

### 3.1.3 *Input Parameters and Assumptions*

*Initial Population,* $N_0$ -- An initial island population estimate was based on extrapolation of cats observed (captures and sighted) from the hunting surveys in March 2012. We first calculated cat density along spotlighting roads. Maximum cat detection distance (the maximum distance a cat could be seen from a road) perpendicular to all spotlighting roads was measured with a Bushnell sport 450 range finder. These areas were then summed to obtain a total sampling area. Total number of cats observed in the sampling area was calculated by adding the number of cats removed to the number of cats that were observed and not shot, so long as there was spatial evidence to support that they were unique. A cat was not considered unique if it was seen within 2.4km of another cat with the same pelage that was not previously shot. A distance of 2.4km was used because that was the maximum distance a cat was observed to travel in one 24-hour period (B. Leo, University of Washington, unpublished data). Cat per unit area was then calculated for the sampling area and then extrapolated to all remaining cat habitat areas. A coefficient of variation (CV) was calculated from the mean and standard deviation of unique cats seen per day ($n$ = 20), and was used to calculate $\sigma_{No}^2$ in eq. 3.5. The extrapolation was calculated with ArcMap 10.1 software.

*Carrying Capacity, K* -- We assume that the feral cat population was at or near carrying capacity before the implementation of the removal program because no island-wide cat removal program existed before February 2012. We therefore equate our $N_0$ to $K$, the carrying capacity for all non-domesticated, feral cat habitat on the island. The parameter $K$ was included as an estimated parameter during the minimization in R.

*Growth rate, r* -- We used fetus count data from cat removal necropsies ($n = 44$) and generation length (Danner 2010) to calculate the maximum possible population growth rate ($r$) defined (eq. 3.7) (Hone 1992)

$$r = \frac{\ln R}{T} \tag{3.7}$$

where $R$ is the net reproductive rate defined as the number of female young produced by a female during its lifetime (May 1981; Crawley 1986) and $T$ is the average age of reproductive females (Millar & Zammuto 1983) or, in general, the mean age of mothers of all newborn females in a population with a stable age distribution (Caughley 1980, Hone 1992). The standard deviation of fetuses per pregnant female was used to calculate $\sigma_r^2$ in eq. 3.6.

*Catchability, q* -- Because hunting was conducted by the field project manager from February 2012 to July 2013 and by technicians from August 2013 to June 2014, catchability was estimated separately for those two time periods. The symbol $q_1$ denotes catchability for the field project manager and $q_2$ denotes catchability for the technician group. Because $q_1$was calculated from consistent data collected by only one individual, we use it for all model projections.

### 3.1.4 *Likelihood Profiles*

To report confidence intervals for $K$ and $q_1$, likelihood profiles were calculated (Hilborn and Mangel 1997). First, the maximum likelihood estimates for $K$ and $q$ were calculated using the likelihood framework described above. Each profile was created by systematically changing the parameter of interest ($K$ or $q_1$), and computing the values of the other parameters that minimized the negative log-likelihood. The parameter values used for $K$ ranged from 500 to 5000 in increments of 1. The parameter values used for $q_1$ ranged from 4.50e-06 to 5.28e-05 in increments of 1.0e-07. Using the likelihood ratio test, the 95% confidence interval is the range of parameters for which the log-likelihood is within 1.92 of the minimum.

### 3.1.5 *Sensitivity Analysis*

The sensitivity of model output to ranges of parameters *r, K,* and $q_1$ were determined using the *sensitivity, Hmisc, ks,* and *pse* packages in R. For *K* and $q_1$, values were randomly selected from a uniform distribution constrained by 95% confidence intervals from likelihood profiles. Values of *r* were drawn from a normal distribution ($\mu$ = .04, σ = .01). . For each parameter combination, the model was run for 18 time steps and output was recorded. The number of time steps was chosen based on the length of time the field project manager was the exclusive hunter. Model output was then graphed as the dependent variable for each parameter.

To ensure sufficient sample size, we calculated the Symmetric Blest Measure of Agreement (SBMA) between the partial correlation coefficients (PCC) of two runs with different sample sizes. We used the sample size that resulted in a SBMA value of 1, which indicates an adequate sample size (Chalom et al. 2013).

Sensitivity was determined by calculating the partial (rank) correlation coefficient, which measures the strength of linear associations between the result and each input parameter after removing the linear effect of the other parameters.

### 3.1.6 *Model Predictions and Cost Benefit Analysis*

Maximum likelihood parameter estimates from the field project manager time period were used to project cat abundance numbers for 24 months. To investigate the effect of increasing effort, we ran the model with four effort levels: the minimum effort of 483 km/month corresponds with the approximate minimum amount of effort needed to prevent a population increase, 1127 km/month corresponds with average number of km driven per month by the field project manager, and the maximum effort of 11587 km/month corresponds to the maximum feasible. The intermediate effort was 1609 km/month.

To assess the cost vs. benefit of hunting control of cats we explored two management strategies over a 24-month time period: 1) a fixed-effort approach consisting of 483 km per month, totaling 11587 km and 2) a strategic-effort approach consisting of an intensive period of 1448 km of removal effort for the 3 months prior to a crow vulnerability period, followed by 161 km per month for all remaining months, totaling 11587 km. The first strategy may be desirable because of its management simplicity. The second strategy is desirable by increasing cat removal prior to periods of high crow vulnerability associated with crow nesting. The crow nesting season typically extends August through February with juveniles fledging beginning in January. We defined the vulnerability period January to July. Cost was measured in km and benefit was measured in removed cats. Cost was equated to time using km driven per hour in order to determine the difference in time spent between strategies. A 95% confidence interval was calculated for time saved per month using a Student’s *t*-distribution.

## 3.2 RESULTS

### 3.2.1 *Population Model*

Model results showed that the population decreased from 1396 in February 2012 to 1060 in July 2013. The population increased from 1048 in August 2013 to 1079 in June 2014 (Figure 3.3). Parameter estimates for model of best fit and 95 % Confidence Intervals are shown in Table 3.1

Table 3.1. Maximum Likelihood Estimates of Model Parameters and Confidence Intervals for Parameters of Interest.

| Parameter | Value | 95 % CI | |
|---|---|---|---|
| | | lower | upper |
| $K$ | 1396 | 716 | 4371 |
| $q1$ | 1.99e-05 | 5.80e-06 | 4.67e-05 |
| $q2$ | 6.10e-06 | | |
| $r$ | 0.04 | | |
| $\sigma_{v1}$ | 0.23 | | |
| $\sigma_{v2}$ | 0.46 | | |
| $N_0$ | 1396 | | |

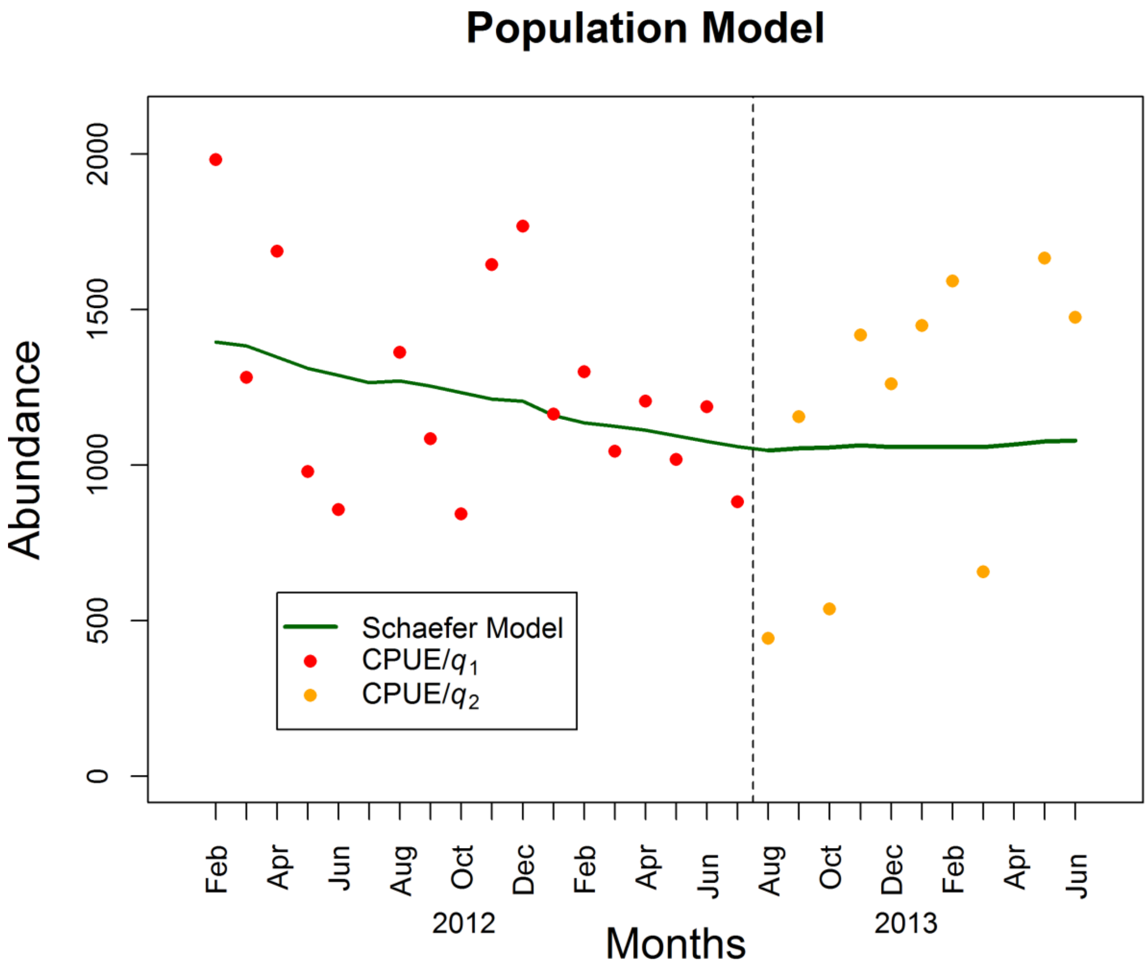

Figure 3.3. Population model for all months of removal effort. Red dots indicate index divided by scaling coefficient, $q_1$. Orange dots indicate index divided by scaling coefficient, $q_2$. Vertical dashed line indicates change in hunting personnel. Green line indicates the Schaefer population model.

### 3.2.2 *Likelihood Profiles*

The limits of the 95% confidence intervals for *K* and $q_1$ were 716 to 4,371 and 4.50e-06 to 5.28e-05 (Figure 3.4), respectively.

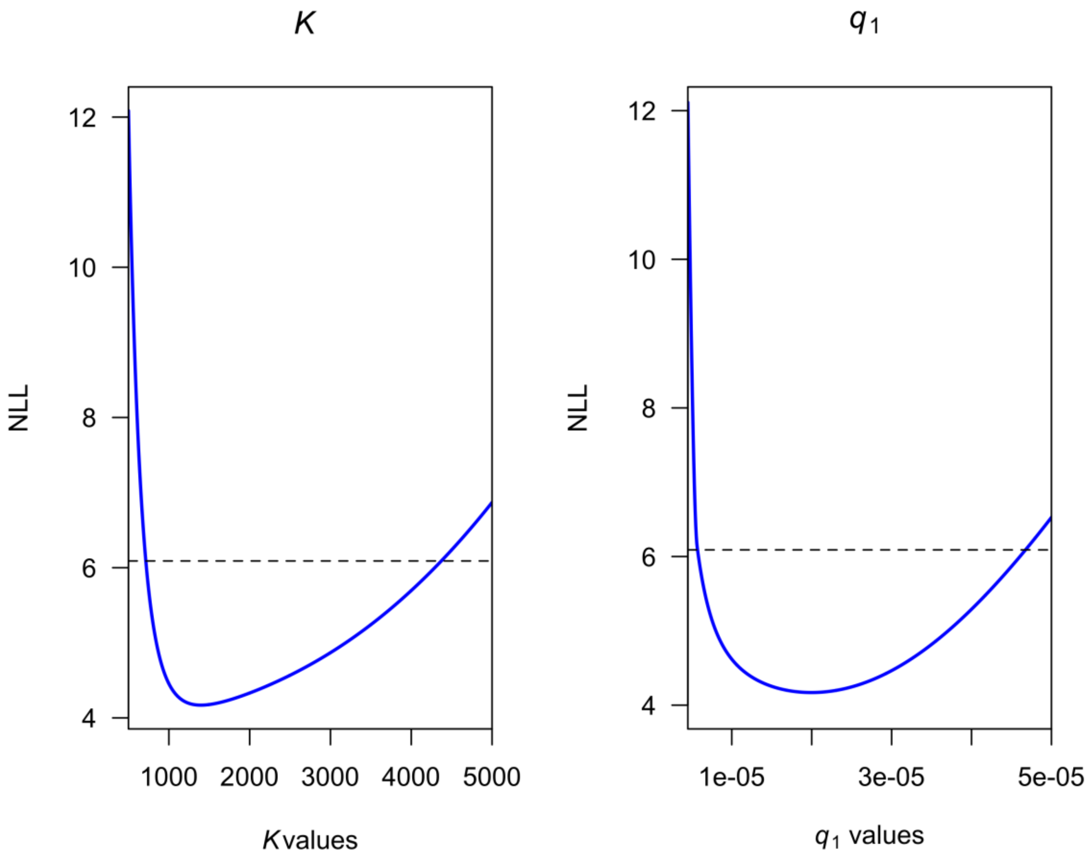

Figure 3.4. Likelihood profiles and Confidence Intervals for *K* and $q_1$.

### 3.2.3 *Sensitivity Analysis*

The SBMA calculations indicated that 300 was an adequate sample size to assess model sensitivity. When each model was run for 18 months, it appeared to be most sensitive to *K* and $q_1$, and marginally sensitive to *r* (Figure 3.5). Partial rank correlation coefficients were lowest for *r* (Table 3.2)

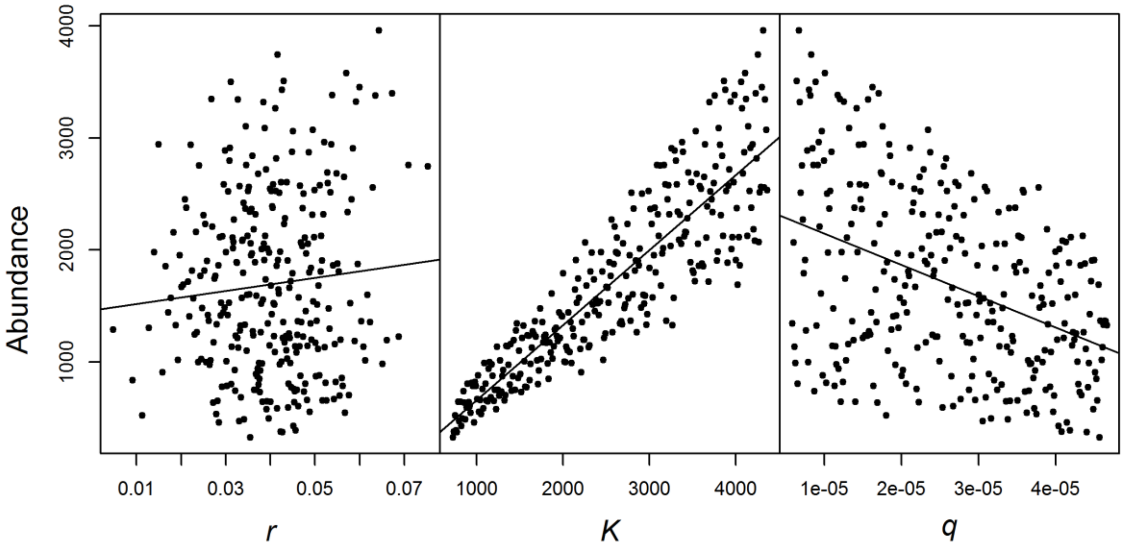

Figure 3.5. Sensitivity analysis of Schaefer model.

Table 3.2. Partial rank correlation coefficients

| Parameter | Value | Std. Error |
|---|---|---|
| *r* | 0.28 | 0.06 |
| *K* | 0.98 | 0.00 |
| *q* | -0.92 | 0.01 |

### 3.2.4 *Model Projections and Cost-Benefit Analysis*

Model projections for a 24 month time period with increasing effort showed varying levels of decreasing abundance (Figure 3.6, Table 3.3).

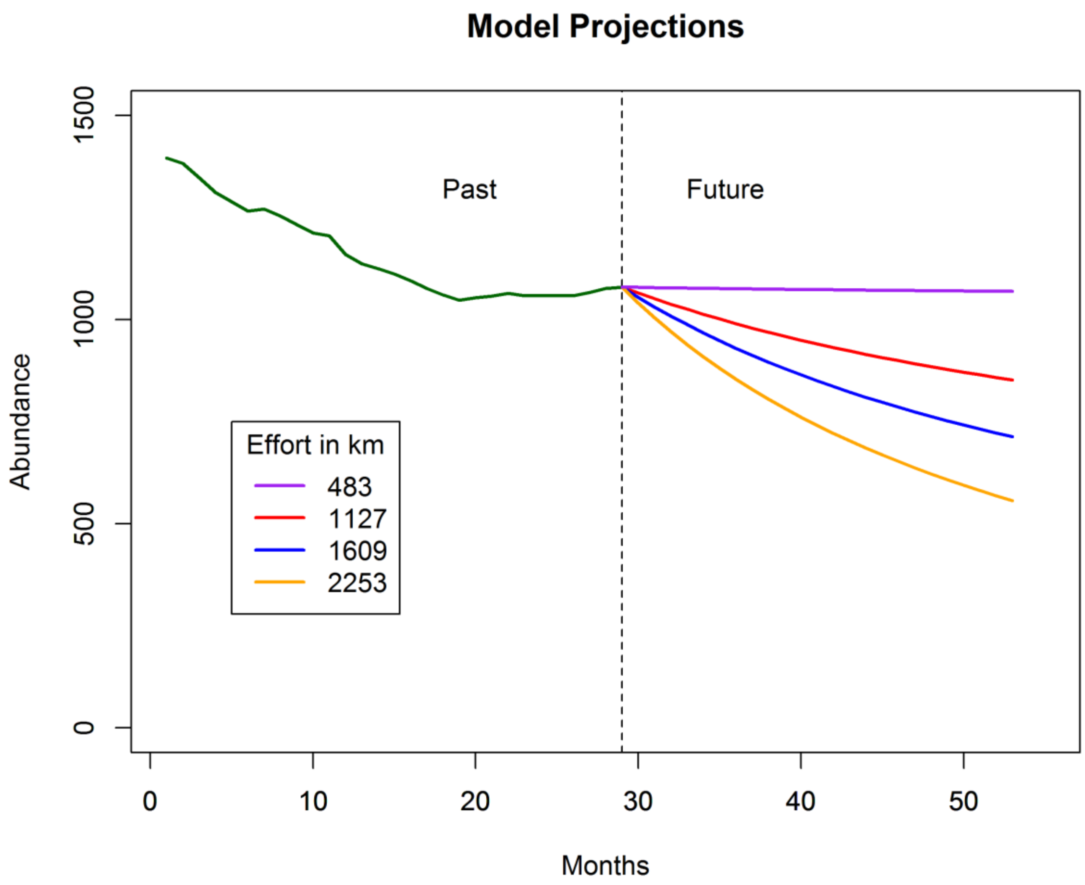

Figure 3.6. Abundance projections (24 months) with four levels of sustained effort. Green line indicates past cat abundance estimates generated from data.

Table 3.3. Projected abundance estimates for respective levels of effort.

| Effort (km) | N(53) |
|---|---|
| 483 | 1069 |
| 1127 | 852 |
| 1609 | 713 |
| 2253 | 557 |

The fixed-effort approach resulted in a steady population, only changing by 4 cats in 24 months. The strategic-effort approach resulted in reduced abundance during vulnerability periods, while still maintaining relatively low cat abundance during less vulnerable periods (Figure 3.7).

Mean km/hr was 17.3 with a 95% confidence interval of ± 1.5. This converts to a mean time of 18.6 hours (95% CI = 17.1, 20.3) that is saved by not driving the extra distance each month.

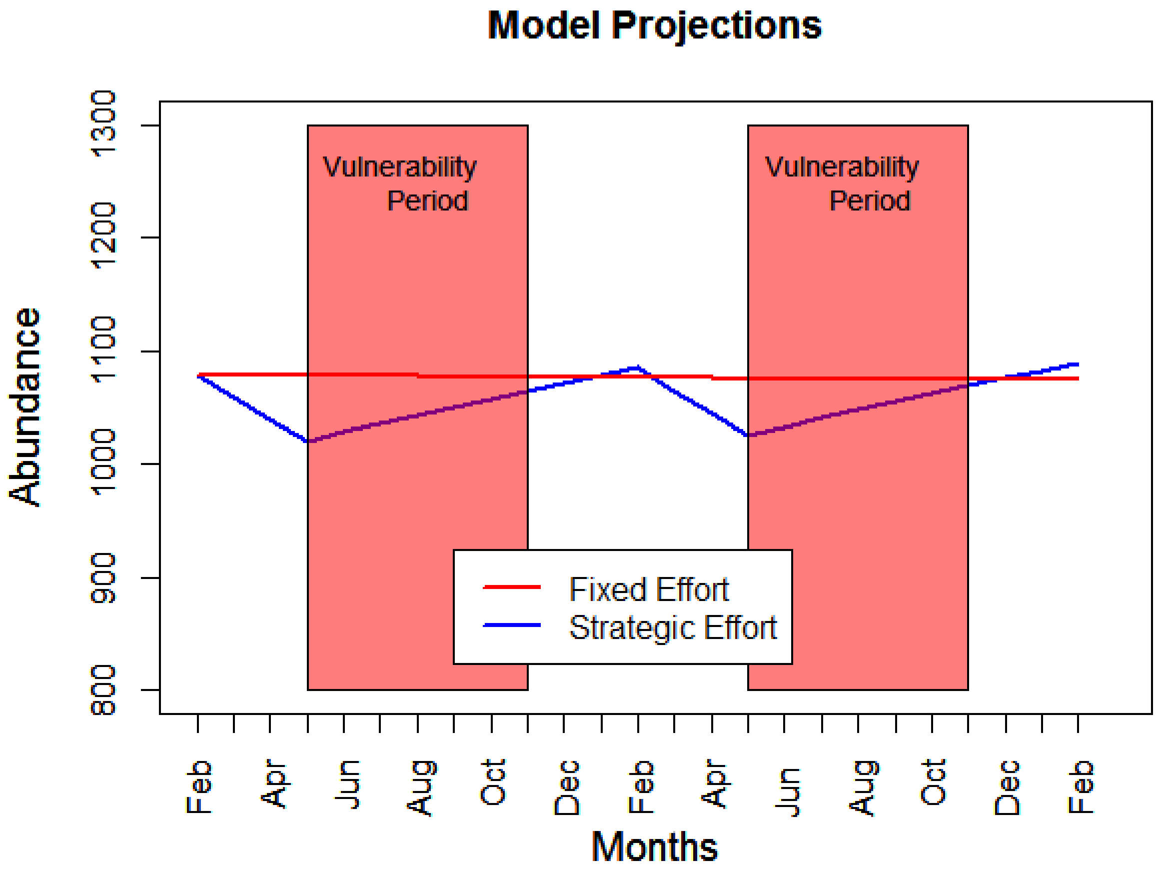

Figure 3.7. Cat abundance for the fixed-effort and strategic-effort approaches.

## 3.3 DISCUSSION

The model was not sensitive to *r*; however, this is likely due to the number and magnitude of time step intervals. If the time increments were annual, then we would expect the model to be more sensitive to $r$. For this reason, it would be prudent to further investigate the reproductive characteristics of the Rota population.

The extreme sensitivity to $K$ can be explained because we equated $N_0$ to $K$ for all model runs. We therefore would expect to see a linear relationship between model outcome and $K$. The model was also sensitive to $q$. Therefore, this parameter should be taken into careful consideration if the model is to be used for future management. As demonstrated above, catchability can vary considerably among personnel and should be estimated accordingly, especially because of its strong influence on model output.

Historically, the removal program on Rota had no criteria with which to apportion spotlight effort levels. Model results presented here provide knowledge and lead to meaningful management implications. This new understanding of the effect of spotlight removal on cat abundance gives reason to consider alternative management strategies; different from the uninform effort approach that has been implemented thus far in the program.

The cost-benefit analysis revealed that some effort strategies although equal in cost, can be more effective than others. The strategic-effort approach would be preferable, because it provides more protection for the crow during periods of increased vulnerability by reducing cat abundance and creating 18.7 more hours per month to be allotted to targeted removal efforts. We emphasize that our vulnerability period is based on the informed opinion of crow biologists, and only represents a hypothetical period of increased vulnerability of juvenile crows. Indeed, juvenile crows are likely more vulnerable for the entirety of their first fledge year, however we assume that vulnerability decreases with time. Here, we use a hypothesized vulnerability period as a way to demonstrate one use of the model. Furthermore, we do not suggest that the strategic-effort approach alone is preferable; rather that it is preferable because it would simultaneously reduce cat numbers while increasing availability of time to be apportioned to auxiliary removal efforts that may further reduce cat numbers during increased vulnerability periods.

Investigations of such removal strategies appear to be particularly warranted, because the model projections (Figure 3.6) show that sustained levels of intense effort do not result in cat extirpation. Even a two-fold increase of sustained effort over a two-year time period resulted in only a difference of 295 cats.

This information should be considered when determining feral cat management objectives on Rota. It would be beneficial to investigate if a cat-density threshold exists for crows, that is, if there is a quantity of feral cat abundance under which crow survival increases. If such a threshold existed, then the Schaefer model could be used to ensure that enough effort is applied to maintain the cat population at levels that promote crow survival.

## 3.4 CONCLUSION

Spotlight removal of feral cats on Rota Island has clear advantages, however it should be used in a strategic fashion and in concert with trapping in order to maximize the protection of the crow. The model showed that applying a constant, intense effort is not necessarily the optimal strategy because intense effort results were similar to those of the lower effort model run. Furthermore, sustained levels of intermediate effort, although capable of maintaining lower cat abundance levels, did not increase crow protection during vulnerability. The analysis represents a straightforward application of the Schaefer model. While more complex population model forms are available we suggest the Schaefer model is well suited for assessing the impacts of limited predator control programs, such as the one conducted on Rota Island. We do suggest that useful information on the effectiveness of the program could be obtained with survey and modeling of the response of the prey species of concern, the Mariana crow in our example.

# Chapter 4. CONCLUSION

This research was necessary in part because of the plastic nature of feral cat populations. The exceptional hunting capabilities of feral cats allow them to persist in almost any environment that supports a prey population. The variability among feral cat populations could be attributed to the myriad of possible prey species they hunt, or the difference in physical characteristics of the geographic locations they occupy. What is certain is that space use, population dynamics, and reproductive output are quite variable among cat populations. It is for this reason that new research must be done on unstudied cat populations in order to inform management strategies.

The primary objective of this thesis is to uncover feral cat behavior on both the individual and population levels in order to inform management strategies on Rota Island. On the individual level, GPS collars were used to gain understanding of daily space use, maximum home range, and differences in space use between sexes. This information is itself useful; it provided the first step for continued space use research on Rota and showed that GPS collars are indeed a viable tool for collecting spatial data. In addition to the Rota-specific findings, the Michaelis-Menten model was uniquely applied to limited home range datasets with the purpose of predicting home ranges. This appears to be a promising technique and could be applied to other populations or perhaps other species entirely.

On the population level, the Schaefer model allows for the speculation of the effect of spotlight removal on the population. Given the findings of chapter 3, spotlight removal does appear to be a feasible and practical way to maintain cat abundance below historic levels. Furthermore, it is plausible that the crow could benefit from a strategic effort approach where more effort is dedicated to spotlight removal prior to crow vulnerability periods.

The Schaefer model described in this thesis provides a tool that can continue to be used to inform management decisions on Rota. As new data accrue, they can be added to the model as a way to monitor the population. As we learn more about crow response to declining cat numbers, we may be able to identify a cat abundance threshold under which crow survival increases. The model provided here would be a good starting point to investigate such a hypothesis.

The model is not without limitations; however, it does appear to match well with the available data. The accuracy of the model could be improved with continued research in reproduction. Future study should be aimed at generation length, as no such data exist for the Rota population; the present study was forced to use an estimate from another population from a foreign, although similar ecosystem.

Predator control on Rota is indeed limited by many factors; however, this research shows that it is possible to reveal the behavior of feral cats. It is encouraging that the removal efforts put forth from February 2012 to June 2014 reduced and maintained cat abundance at lower levels, despite the complete lack of previous cat research on Rota. This research will contribute to the improvement of the control project and hopefully lead to a successful recovery of the endangered Mariana crow.

# BIBLIOGRAPHY

Amar, A., F. Amidon, B. Arroyo, J.A. Esselstyn, and A.P. Marshall 2008. Population trends of the forest bird community on the Pacific island of Rota, Mariana Islands. The Condor 110(3):421-427.

Blackburn, T. M., P. Casey, R. P. Duncan, K. L. Evans, and K. J. Gaston. 2004. Avian Extinction and Mammalian Introductions on Oceanic Islands. Science 305: 1955-1958

Boydston, E. E., K. M. Kapheim, M. Szykman, and Kay Holekamp. 2003. Individual variation in space use by female spotted hyenas. Journal of Mammalogy 84: 1006-1018.

Burrows, N. D., D. Algar, A. D. Robinson, J. Sinagra, B. Ward, and G. Liddelow. 2003. Controlling introduced predators in the Gibson Desert of Western Australia. Journal of Arid Environments 55:691-713.

Caughley, G. (1977). Analysis of vertebrate populations.

Chalom, A., C.Y. Farmer, and P.I. Prado. 2013. Sensitivity Analyses: a brief tutorial with R package pse. Version 0.3.1

Courchamp, F., and Sugihara, G. 1999.  Modeling the biological control of an alien predator to protect island species from extinction. Ecological Applications. 9:112-123.

Crawley, M. J., H. Kornberg, J. H. Lawton, M.B. Usher, R. Southwood, R.J. O'Connor, and A. Gibbs. 1986. The population biology of invaders [and discussion]. Philosophical Transactions of the Royal Society B: Biological Sciences 314(1167):711-731.

Danner, R. M., C. Farmer, S. C. Hess, R. M. Stephens, and P. C. Banko. 2010. Survival of Feral Cat, *Felis catus* (Carnivora: Felidae), on Mauna Kea, Hawai'I, Based on Tooth Cementum Lines. Pacific Science 64:381-389.

Edwards, G. P., N. De Preu, B. J. Shakeshaft, I. V. Crealy, and R. M. Paltridge. 2001. Home range and movements of male feral cats (*Felis catus*) in a semiarid woodland environment in central Australia. Austral Ecology 26:93-101.

Fancy, S. G., M. R. Lusk, and D. Grout. 1999. Status of the Mariana crow population on Rota, Mariana Islands. Micronesica 32:3-10.

Fitzgerald, B. M., and B. J. Karl. 1986. Home range of feral house cats (*Felis catus* L.) in forest of the Orongorongo Valley, Wellington, New Zealand. New Zealand Journal of Ecology 9:71-82.

Falanruw, M. C., T. G. Cole, and A. H. Ambacher. 1989. Vegetation survey of Rota, Tinian, and Saipan, Commonwealth of the Northern Mariana Islands. Pacific Southwest Forest and Range Experiment Station Resource Bulletin.

Fritts, T. H., and E. M. Taisacan. 1990. Abundance and habitat use of reptiles on Rota, Mariana Islands. Micronesica 23:153-166.

Goltz, D. M., S. C. Hess, K. W. Brinck, P. C. Banko, and R. M. Danner. 2008. Home range and movements of feral cats on Mauna Kea, Hawai ‘i. Pacific Conservation Biology 14:177-184

Harper, G. A. 2007. Habitat selection of feral cats (*Felis catus*) on a temperate, forested island. Austral Ecology 32:305-314.

Herfindal, I., J. D. C. Linnell, J. Odden, E. B. Nilsen, and R. Anderson. 2005. Prey density, environmental productivity and home-range size in the Eurasian lynx (*Lynx lynx*). Journal of Zoology 265:63-71.

Hilborn, R. , and M. Mangel. 1997. The ecological detective: confronting models with data. Vol. 28. Princeton University Press.

Iverson, J. B. 1978. The impact of feral cats and dogs on populations of the West Indian rock iguana, (*Cyclura carinata*). Biological Conservation 14:63-73.

Jones, E., and B. J. Coman. 1982. Ecology of the Feral Cat, *Felis catus* (L.), in South-Eastern Australia. 3. Home Ranges and Population Ecology in Semiarid North-West Victoria. Australian Wildlife Research 9:409-420.

Kenward, R. E. 2001. A manual for wildlife radio tagging. Academic Press, London, UK.

King, W.B. 1985. Island birds: will the future repeat the past? Pages 3-15 in P.J. Moors, editor. Conservation of island birds. ICBP Technical Publication Number 33.

Konecny, M. J. Home range and activity patterns of feral house cats in the Galapagos Islands. Oikos 50:17-23.

Litvaitis, J. A., J. A. Sherburne, and J. A. Bissonette. 1986. Bobcat habitat use and home range size in relation to prey density. The Journal of Wildlife Management 50:110-117.

Martin, J., B. Rey, J. Pons, E. Natoli, and D. Pontier. 2013. Movements and space use of feral cats in Kerguelen archipelago: a pilot study with GPS data. Polar Biology 36:1531-1536.

McCarthy, R. J., S.H. Levine, and J.M. Reed. 2013. Estimation of effectiveness of three methods of feral cat population control by use of a simulation model. Journal of the American Veterinary Medical Association 243(4): 502-511.

Medina, F. M., E. Bonnaud, E. Vidal, B. R. Tershy, E. S. Zavaleta, C. J. Donlan, B. S. Keitt, M. Le Corre, S. V. Horwath, and M. Nogales. 2011. A global review of the impacts of invasive cats on island endangered vertebrates. Global Change Biology 17:3503-3510.

Michaelis, L., and M. L. Menten. 1913. Die kinetik der invertinwirkung. Biochemistry Z 49:333-369. [In German]

Millar, J. S., and R.M. Zammuto. 1983. Life histories of mammals: an analysis of life tables. Ecology, 631-635.

Mitchell, N., R. Haeffner, V. Veer, M. Fulford-Gardner, W. Clerveaux, C. R. Veitch, and G. Mitchell. 2002. Cat eradication and the restoration of endangered iguanas (*Cyclura carinata*) on Long Cay, Caicos bank, Turks and Caicos Islands, British West Indies. Turning the tide: the eradication of invasive species. World Conservation Union, Gland, Switzerland.

Molsher, R., C. Dickman, A. Newsome, and W. Müller. 2005. Home ranges of feral cats (*Felis catus*) in central-western New South Wales, Australia. Wildlife Research 32:587-595.

Moors, P. J., and I.A.E. Atkinson. 1984. Predation on seabirds by introduced animals, and factors affecting its severity. New Zealand Wildlife Service.

Mueller-Dombois, D., and F. R. Fosberg. 1998. Vegetation of the Tropical Pacific Islands. Springer, New York.

Nogales, M., A. Martin, B. R. Tershy, C. J. Donlan, D. Veitch, N. Puerta, B. Wood, and J. Alonso. 2004. A review of Feral Cat Eradication on Islands. Conservation Biology 18:310-319.

Norbury, G. L., D. C. Norbury, and R. P. Heyward 1998. Space use and denning behaviour of wild ferrets (*Mustela furo*) and cats (*Felis catus*). New Zealand Journal of Ecology 22:149-59.

Pierce, B. M., V. C. Bleich, and R. T. Bowyer. 2000. Social organization of mountain lions: does a land-tenure system regulate population size? Ecology 81:1533-1543.

Plentovich, S., J. M. Morton, J. Bart, R. J. Camp, M. Lusk, N. Johnson, and E. Vanderwerf. 2005. Population trends of Mariana Crow *Corvus kubaryi* on Rota, Commonwealth of the Northern Mariana Islands. Bird Conservation International 15:211-224.

Powell, R. A., J. W. Zimmerman, and D. E. Seaman. 1997. Ecology and behaviour of North American black bears: home ranges, habitat, and social organization. Volume 4. Springer Science & Business Media.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Recio, M. R., R. Mathieu, P. Denys, P. Sirguey, P. J. Seddon. 2011. Lightweight Global Positioning System Tags, One Giant Leap for Wildlife Tracking? An Assessment Approach. PLoS one 6:e28225.

Recio, M. R., R. Mathieu, R. Maloney, and P. J. Seddon. 2010. First results of feral cats (*Felis catus*) monitored with Global Positioning System collars in New Zealand. New Zealand Journal of Ecology 34:288-296

Recio, M. R., and P. J. Seddon. 2013. Understanding determinants of home range behaviour of feral cats as introduced apex predators in insular ecosystems: a spatial approach. Behavioral Ecology and Sociobiology 67:1971-1981.

Robertson, S. A. 2008. A review of feral cat control. Journal of Feline Medicine and Surgery. 10(4):366-375.

Rodríguez, C., R. Torres, and H. Drummond. 2006. Eradicating introduced mammals from a forested tropical island. Biological Conservation 130:98-105.

Ross, S., B. Munkhtsog, and S. Harris. 2012. Determinants of mesocarnivore range use: relative effects of prey and habitat properties on Pallas's cat home-range size. Journal of Mammalogy 93:1292-1300.

Salo, P., E. Korpimäki, P. B. Banks, M. Nordström, and C. R. Dickman. 2007. Alien predators are more dangerous than native predators to prey populations. Proceedings of the Royal Society B: Biological Sciences 274:1237-1243.

Schoener, T. W. 1981. An empirically based estimate of home range. Theoretical Population Biology 20:281-325.

Taylor, R. H. 1979. How the Macquarie Island parakeet became extinct. New Zealand Journal of Ecology 42-45.

Van Aarde, R. J. 1983. Demographic parameters of the feral cat *Felis catus* population at Marion Island. South African Journal of Wildlife Research 13:12-16.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. Melillo. 1997. Human domination of Earth's ecosystems. Science 277:494-499.

Wiewel, A. S., A. A. Y. Adams, and G. H. Rodda. 2009. Distribution, Density, and Biomass of Introduced Small Mammals in the Southern Mariana Islands 1. Pacific Science 63:205-222.