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Salt marsh harvest mouse abundance and site use in a managed marsh

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SALT MARSH HARVEST MOUSE ABUNDANCE AND SITE USE IN A MANAGED MARSH

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by

Galli Basson

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SALT MARSH HARVEST MOUSE ABUNDANCE AND SITE USE IN A MANAGED MARSH

by
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ABSTRACT

SALT MARSH HARVEST MOUSE ABUNDANCE AND SITE USE IN A MANAGED MARSH

by Galli Basson

The salt marsh harvest mouse (*Reithrodontomys raviventris*) is a federal and California listed endangered mammal endemic to the San Francisco Bay. The objectives of this research were to determine habitat use of endangered salt marsh harvest mice in a managed marsh in Fremont California, and to evaluate whether managed flooding of the marsh provides favorable habitat conditions for the mice. In addition, this research explores the effectiveness of using mark-recapture model selection analysis to estimate capture probability, survival, and population growth rate for salt marsh harvest mice.

Mice were captured for four nights per month between May and August, 2008. Thirty-six unique salt marsh harvest mice were captured for a catch per 100 nights of trap effort of 1.9. The sex ratio of male to female mice was skewed towards males with a sex of 2.3:1. Salt marsh harvest mice were distributed randomly throughout the marsh and no relationships were found between mice distribution and pickleweed salinity, pickleweed height, distance to levees, distance to dry or filled water bodies, percent cover of vegetation, or sympatric rodents. The findings of this study indicate that catch-per-trap-effort, the current standard method to estimate salt marsh harvest mice populations, may not be accurate. The results of this study can be used by managers of salt marsh harvest mice habitat to manage and estimate mouse populations.

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Introduction

Salt marsh harvest mice (*Reithrodontomys raviventris*) are endemic to the salt and brackish marshes of the San Francisco Bay. This species was listed as endangered in 1970 by the U.S. Fish and Wildlife Service and in 1971 by the California Department of Fish and Game. Habitat loss is the primary factor in the decline of this species (Shellhammer et al., 1982). Tidal marsh habitat used by the salt marsh harvest mouse (SMHM) in the San Francisco Bay area has declined by approximately 90% of its former extent due to urban development, agriculture, salt pond production, or subsidence (Shellhammer et al., 1982). The major threats to tidal-marsh vertebrates in the Bay include habitat loss (habitat fragmentation, sediment availability, and sea-level rise), deterioration (contaminants, water quality, and human disturbance), and competitive interactions (invasive species, predation, mosquito control, and disease) (Takekawa et al., 2006). Much of the remaining SMHM habitat consists of diked and muted marshes that are small, fragmented, and isolated. Diking and filling of marsh habitat has altered marsh hydrology and salinity, further degrading the available habitat.

Related Research

The salt marsh harvest mouse is a small, endemic rodent found in the salt and brackish marshes of the San Francisco Bay. There are two subspecies of salt marsh harvest mice. The northern subspecies *R. r. halicoetes* is endemic to the North Bay and ranges from the Marin Peninsula through the marshes of Napa and Suisun Bay. The southern subspecies *R. r. raviventris* is found along the San Francisco Peninsula from San Mateo County to the southern end of the Bay, and along the eastern side of the Bay near Newark.

Salt marsh harvest mice are small mammals, ranging in total length from 118 to 175 mm and in weight from 8 to 14 grams. Both subspecies are adapted to live in salt marshes and can swim and drink salt water (Fisler, 1965). Salt marsh harvest mice are largely vegetarians, consuming green vegetation and seeds (Fisler, 1965). The breeding season of the southern subspecies for males is from April to September, with the highest breeding percentage in July, and for females is March though November (Fisler, 1965). The primary breeding season for the northern subspecies is June through September for males and August through November for females (Bias, 1994). Neither subspecies burrows, but the northern subspecies is known to build nests that can be rebuilt quickly on the ground surface. There is not much information about the nesting behavior of the southern subspecies, although it is believed they do little nest building (Shellhammer, 1982). The southern subspecies has four offspring per litter with one or two litters per breeding season. SMHM typically do not live longer than nine months (Fisler, 1965).

Historically, SMHM were found throughout the marsh, ranging from the upper limits of the marshes to the edge of the Bay (Fisler, 1965). SMHM were more prevalent near natural levees in the marsh. Overhead cover was important to survival and the mice moved into the grasslands during the summer months when the cover was higher (Fisler, 1965). Today, many of the marshes in the South Bay are diked off from the Bay, eliminating tidal action (Shellhammer, 1989). Most marshes have been reduced to narrow strips that are hypersaline diked areas with reduced plant diversity and cover (Zetterquist, 1977).

Currently SMHM are typically found in pickleweed (*Sarcocornia* sp.) habitat, which is found at mid-to-high marsh elevations. Pickleweed is an important component of SMHM habitat selection as the mice use it for food and as protective cover from predators (Fisler, 1965). Pickleweed habitat value rises with increasing depth, density, and degree of intermixing with fat hen (*Atriplex patula*), alkali heath (*Frankenia grandifolia*), and other mid to high marsh plant species (Shellhammer et al., 1982; Wondolleck & Zolan, 1976). However, several other studies reported SMHM in areas not dominated by pickleweed (Botti, Warenycia, & Becker, 1986; Rice, 1974), indicating that pickleweed cover is not the only important micro-habitat feature influencing SMHM presence. The 1984 USFWS Recovery Plan characterizes the optimal habitat for SMHM as having 100 percent cover, a cover depth of 30 to 50 cm during the summer, greater than 60 percent pickleweed cover, and habitat complexity which includes salt bush (*Atriplex patula*) and alkali heath (*Frankenia* sp.).

The loss of tidal marshes and the conversion of the remaining habitat by diking and filling have resulted not only in a smaller range for the mice, but also in degraded and fragmented habitat. Although habitat loss is the primary reason for SMHM decline, habitat fragmentation can have negative effects via edge effects and inhibition of dispersal (Takekawa et al., 2006). These negative effects can produce negative synergistic impacts on SMHM populations by increasing competition and predation. For instance, the house mouse (*Mus musculus*), an invasive species, uses habitat that is more patchily distributed than SMHM, which may result in the displacement of the SMHM from available habitat (Bias & Morrison, 2006).

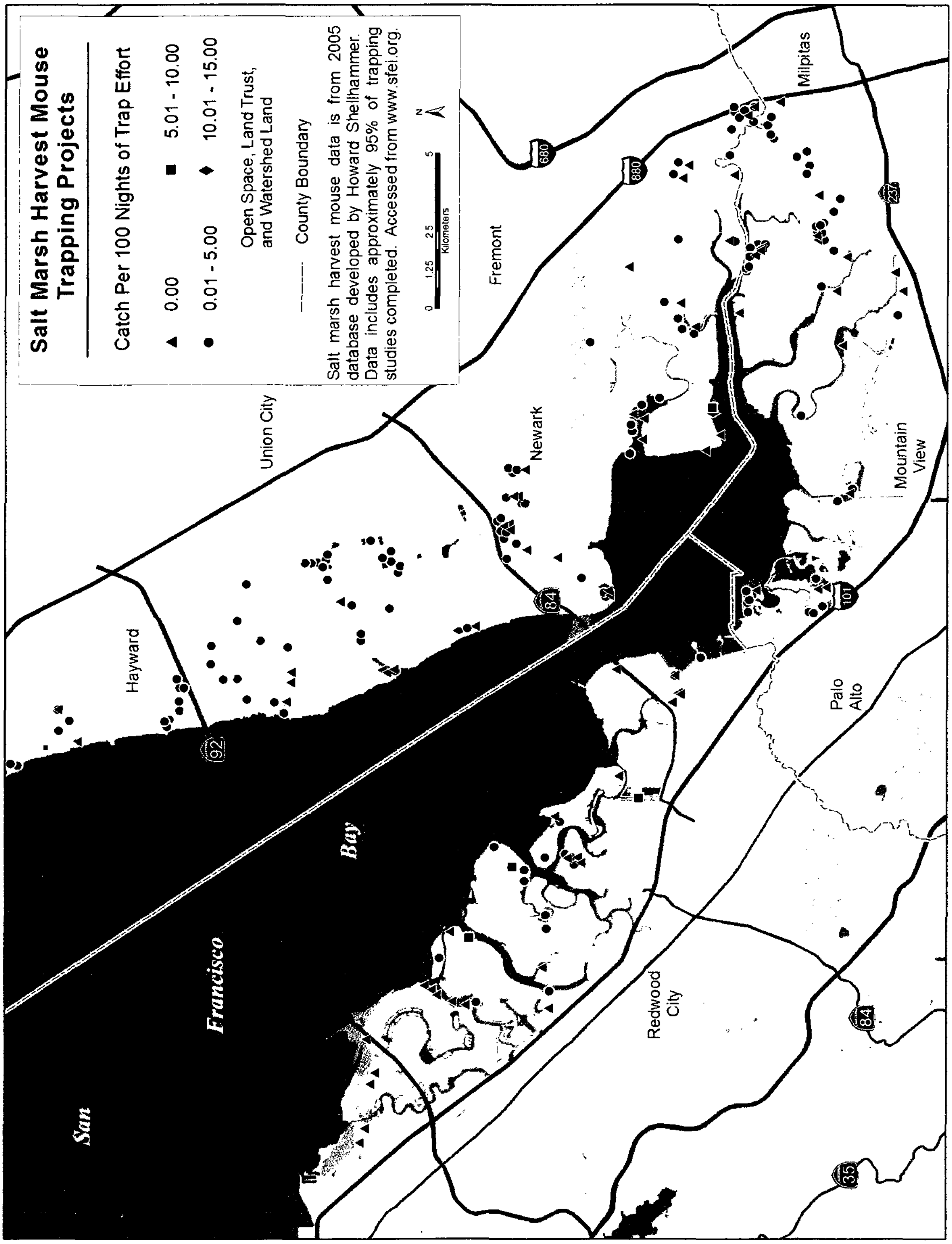
Salt marsh harvest mice need habitat for foraging, nesting, and cover from predators. An important feature of optimal habitat is connectivity to upland areas so that SMHM have refugia during the highest high tides (Shellhammer et al., 1982; Wondolleck & Zolan, 1976). Roads, levees, urban development, and non-native vegetation have replaced upland edges and transition zones, negatively affecting animals that rely on these areas for high-tide refuge. Hadaway and Newman (1971) found that SMHM were trapped on levees in higher numbers when the marsh was flooded. Levees do not provide the same vegetative cover found in the marsh and can increase the risk of predation.

Habitat of sufficient size to support self-sustaining salt marsh harvest mouse populations must now factor in challenges such as sea level rise. The USFWS is currently drafting the Tidal Marsh Species Recovery Plan which will specify the amount of marsh area necessary to support SMHM populations. Marshes should have extensive pickleweed coverage, a high marsh transition area, and stands of gumweed (*Grindelia*) or tall pickleweed interspersed with shorter forms of pickleweed to provide high tide refugia. In addition, large marsh complexes should be connected by corridors to allow movement of mouse populations (Valary Bloom, personal communication, February 11, 2009).

The alteration of tidal marshes due to diking and filling results in salinity changes. Pickleweed changes seasonally in salinity, water content, morphology, and anatomy and the amount of change varies depending on whether the marsh is diked off from the Bay or fully tidal (Omer, 1994). Thus, water management is a critical factor in creating beneficial pickleweed micro-habitat environment for the SMHM. In highly altered diked marshes, Zetterquist (1977) found SMHM in marshes with very high levels of water and pickleweed salinity, although she does not publish the pickleweed salinity levels. Whether the mice prefer highly saline habitat or use it to avoid competitors is not known. Geisel et al. (1988) found the pickleweed salinity level to range between 97 ppt and 139 ppt and concluded that SMHM were superior competitors to California voles in the most saline areas or saline periods during the yearly cycle of an average diked marsh. Both Zetterquist's and Geisel et al.'s results differ from recent studies. Kingma (2003) found mice in areas of low and moderate levels of pickleweed salinity (65-85 ppt), but absent in areas with high pickleweed salinity levels. Padgett-Flohr and Isakson (2003) found SMHM associated with mid-range pickleweed salinity levels (500-699 mmol/kg Cl^-), were rare in hyper-saline areas (699 mmol/kg Cl^-), and were not found at all in areas of low salinity (200-499 mmol/kg). Since pickleweed can grow in freshwater marshes, monitoring marshes solely for pickleweed presence without including salinity may be misleading to managers. There is a need to clarify conflicting past research on SMHM and salinity associations.

Studies examining the relationship between SMHM and sympatric rodent species have also yielded conflicting results. Geissel et al. (1988) found California voles (*Microtus Californicus*) can push house mice and SMHM into marginal habitats or local extirpation. Bias & Morrison (2006) found positive associations between California vole presence and habitat parameters such as vegetative cover, but negative associations with California vole and water presence and depth; they recommend restoration of tidal action to reduce California vole competition. Padgett-Flohr and Isakson (2003) found no statistical associations between California voles and SMHM, although they did catch California voles in the same areas as SMHM. Padgett-Flohr and Isakson (2003) caught few house mice and attributed the low numbers of house mice to the high quality of their study area as house mice are usually associated with disturbed areas and proximity to human development. Bias & Morrison (2006) recommend reducing habitat patchiness to limit house mice. Shellhammer et al. (1982) noted that SMHM use border grassy areas connected to the marsh but are seldom found in extensive grassy areas, which is the primary habitat of the western harvest mouse (*Reithrodontomys megalotis*).

There are no estimates of the current population size of SMHM in the South Bay, as research is usually conducted in isolated locations and in different years (Figure 1). Instead, SMHM estimates are usually compared from year to year or from one location to another to determine if the population is increasing or decreasing in a given area. Each study represented on the map (Figure 1) represents a relative estimate of the population at that location during the year the study was conducted. Thus, biologists are not able to estimate the SMHM population throughout the Bay, or even if the population as a whole is increasing or decreasing.



Salt marsh harvest mouse data is from 2005 database developed by Howard Shellhammer. Data includes approximately 95% of trapping studies completed. Accessed from www.sfei.org.

Figure 1. Trapping studies of SMHM in the South Bay between 1971 and 2005.

The U.S. Fish and Wildlife Service (USFWS) manages the Don Edwards National Wildlife Refuge in the South San Francisco Bay, CA, which provides habitat for the southern subspecies of SMHM. Proper management and restoration of remaining salt marsh harvest mouse habitat is critical to the survival of this highly endangered species. One of the areas that the USFWS actively manages for SMHM is the 10.1 ha (25-acre) Warm Springs Mouse Pasture (WSMP) in south Fremont, CA. The USFWS assumed management of the parcel in 1987 as mitigation for the development of the Bayside Business Park. The WSMP alone is not large enough to support a viable population of SMHM, but it is an important habitat within the larger marsh network. The management objective of the WSMP is to provide suitable, occupied habitat for SMHM. Specifically, the goals of the WSMP are to increase SMHM density and pickleweed cover, reduce grass cover, and manage the water during the pickleweed growing season for pickleweed cover (Buffa, 2004). Refuge managers need more research on the status of the SMHM population at the WSMP and on whether the objectives listed in the water management plan are being met.

Basic life history traits, such as SMHM survival, recruitment, emigration, immigration, and age ratios, are unknown. Existing data on litter size, nesting behavior, foraging behavior, and life span come mainly from Fisler's 1965 study. Tools for endangered species management typically rely on demographic parameters. An example of one tool commonly used is Population Viability Analysis (PVA) (Reed et al., 2002). Although PVA models vary, they require an understanding of demographic parameters such as reproduction rate, life span, and dispersal, in order to be useful (Beissinger &

Westphal, 1998). Previous research completed on SMHM varies in location and time, and most studies are brief, ranging from several days to a few months (Shellhammer, 1989), with the exception of one multi-year study in the North Bay (Bias, 1994). The use of piecemeal studies using different experimental designs and locations makes comparisons among studies difficult (Padgett-Flohr & Isakson, 2003). In addition, methodological and statistical problems pervade in previous research, where trapping sites are typically selected in a non-random and unverified manner based on the investigator's subjective perception of marginal or optimal habitat (Geissel, Shellhammer, & Harvey, 1988; Rice, 1974; Zetterquist, 1977).

Salt marsh harvest mouse abundance is currently estimated using the relative abundance index catch per trap effort (CPTE) (Shellhammer & Padgett-Flohr, 2002). An index is an indirect measurement used when the relationship between the desired and measured data differ but are functionally related (McKelvey & Pearson, 2001). Catch per trap effort allows relative comparisons between sites with different numbers of traps and studies that vary temporally. One important assumption of an index is constant probability of detection, an assumption that may be violated if animals are either trap shy, trap happy, exhibit individual capture probability differences based on age, sex, or other characteristics, or if the probability of detection varies with time (Menkens & Anderson, 1988; Otis, Burnham, White, & Anderson, 1978).

Statistical models have been developed based on capture-recapture models in order to estimate animal abundance when individuals exhibit different probabilities of detection. Although capture-recapture models are preferable to indices based on simulations and statistical theory (Nichols & Pollock, 1983), sample size constraints are the reason researchers use indices instead of estimators (White, 2005). Although indices can provide useful information regarding small mammal habitat use and management response, the assumption of constant probability of detection must be validated before an index can be used for population comparisons (McKelvey & Pearson, 2001). Indices are often biased because they use count data that is assumed to be proportional to population size, an assumption which is seldom verified and often false (White, 2005). Only one multi-year study analyzed survival for *R. r. haliocetes* (Bias, 1994), and no multi-year studies have been done with *R. r. raviventris*. There are no analyses of *R. r. raviventris* that estimate variation in capture probabilities, capture and recapture probabilities, and survival probabilities. Current abundance estimates do not provide demographic information which are essential for management success such as estimation of survival rate, detection probability of SMHM, and lambda. Lambda, or the finite rate of population change, is a parameter that indicates for every individual present during the time interval sampled, there will be X number of individuals the following time interval. If lambda is >1, the population is increasing, if < 1 the population is decreasing, and if lambda =1 the population is static (Franklin, 2001).

Research Objectives

The overall objective of this research was to pilot the use of mark and recapture model selection analysis to estimate capture probability, recapture probability, survival, and population growth rate in SMHM at the WSMP. This research also evaluates whether managed flooding of the WSMP between 2004 and 2008 provided favorable habitat conditions for SMHM. Finally this work evaluates current salt marsh harvest mouse estimation methods and compares them with mark and recapture model selection methods used in this study.

Specifically, this research tests two hypotheses and six research questions:

Hypothesis 1:

H_O: There is no relationship between capture site parameters, including pickleweed height, pickleweed salinity, percent cover of vegetation, distance to levee, distance to nearest dry or filled water body, and SMHM abundance or the abundance of other rodent species.

Hypothesis 2:

H_O: Pickleweed salinity does not vary over the 4 month summer period (May – August) of this study at the WSMP.

Research Questions:

1. What are the site characteristics of the WSMP and how do these characteristics compare to favorable/high quality conditions as found by other researchers and described in the USFWS 1984 Recovery Plan?

2. How are the mice distributed within the WSMP based on capture site parameters and sympatric rodent species?

3. What is the population estimate of salt marsh harvest mouse at the WSMP, how has the population estimate changed over time, and how does the population estimate compare to other locations?

4. Can we estimate capture-recapture probabilities, survival probability, and population growth rate for SMHM?

5. How well do current salt marsh harvest mouse population estimation methods work?

Knowledge of SMHM site use and demographics are vital to U.S. Fish and Wildlife Service and California Department of Fish and Game managers as they seek to make decisions that benefit SMHM. Specifically, the findings of this research are designed to assist Refuge managers with meeting the goals of the Warm Springs Mouse Pasture Water Management Plan (Buffa, 2004) as well as the USFWS Salt Marsh Harvest Mouse Recovery Plan, which aims to protect and increase SMHM populations through the creation of new habitat, restoration of former habitat, and research into habitat requirements and population trends (USFWS, 1984).

My study is focuses on site use of SMHM at the WSMP and results may not be reflective of site use at other locations. Successful recovery and management of SMHM require a multi-year study (USFWS, 1984). However, this 4-month study is intended to pilot the use of mark-recapture techniques and model selection for SMHM population parameters. This research does not provide information on any other factors that may influence site use, including predation or forage amount.

Study Site

The 10.1 hectare (25 acre) WSMP in south Fremont, California (Figure 2) is a diked wetland located in the Don Edwards San Francisco Bay National Wildlife Refuge owned and managed by the USFWS. The WSMP is managed to provide habitat for SMHM (Buffa, 2007b). The WSMP is bound by levees on all four sides. Water intake from the Coyote Creek Lagoon is manually controlled by two tide gates. There are 3,250 linear feet of ditches that circulate water throughout the Mouse Pasture. The dominant vegetation at the site consists of pickleweed. There is small lagoon located on the east side of the WSMP. A business park is located across the levee bordering the northeast side of the site, the Coyote Creek Lagoon borders the west side, and there is a restored muted tidal marsh on the south side located across a channel.

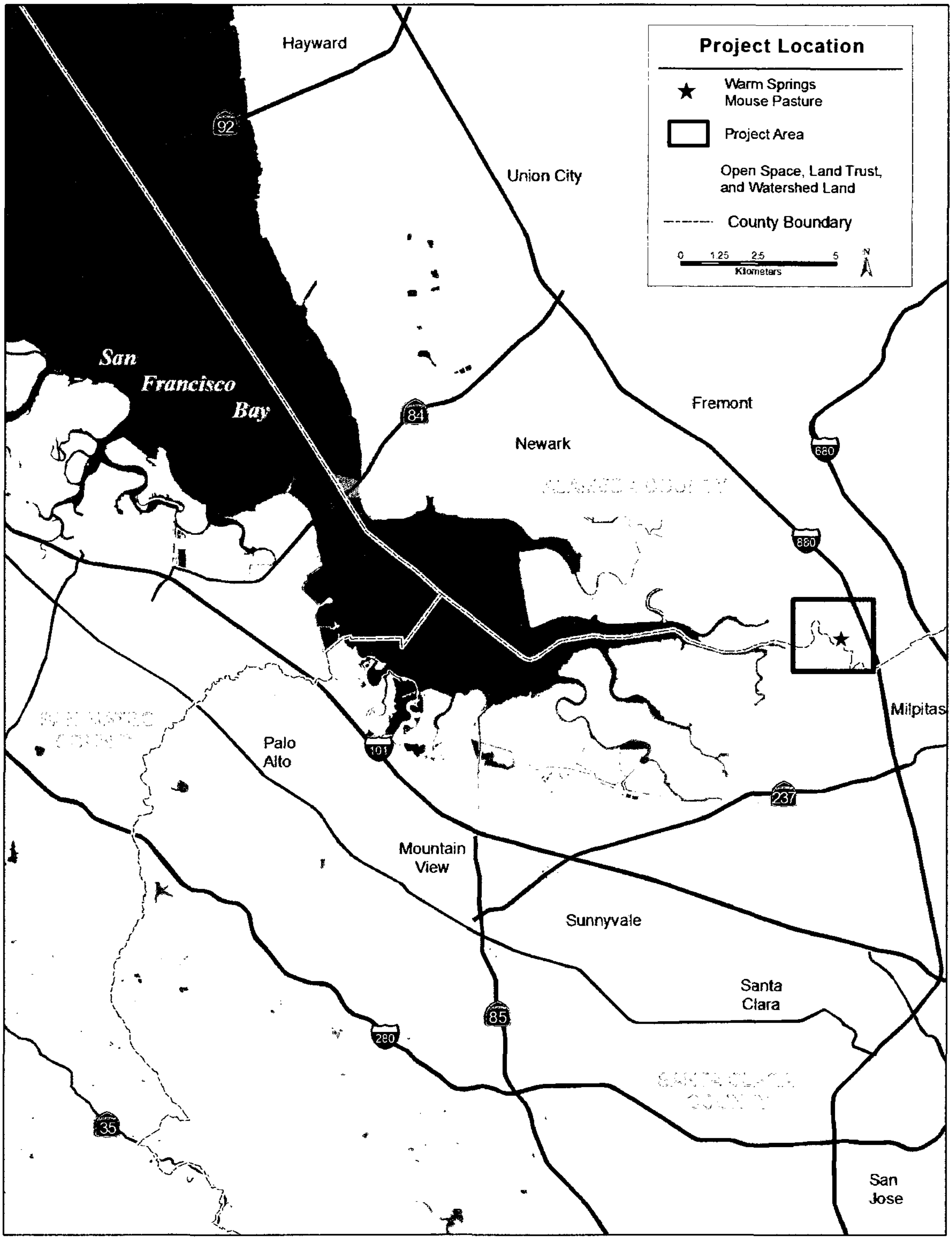


Figure 2. Location of Warm Springs Mouse Pasture in Fremont, CA

Methods

I conducted my field research from May to August 2008. I choose sample sites using ArcGIS 9.2 (ESRI, Redlands, CA, USA) by creating a shapefile of the WSMP using an aerial photograph as a guide, and using Hawth's Tools (Beyer, 2004) to randomly select 40 sites within that shapefile. I then located each site in the field with a Trimble GPS unit (Figure 3). I placed a flag at each site and three additional flags in a triangle formation approximately one meter away from the center flag, indicating the location of the traps (Figure 4). I set a total of 120 Sherman live traps each night, following the methodology of Padgett-Flohr and Isakson (2003). The purpose of using 3 traps at each site is to try to capture different species that utilize the same area. If more traps are available per site, the data recorded for the site may be more accurate in capturing the rodent species composition at that site, particularly if one species is more easily caught than others.

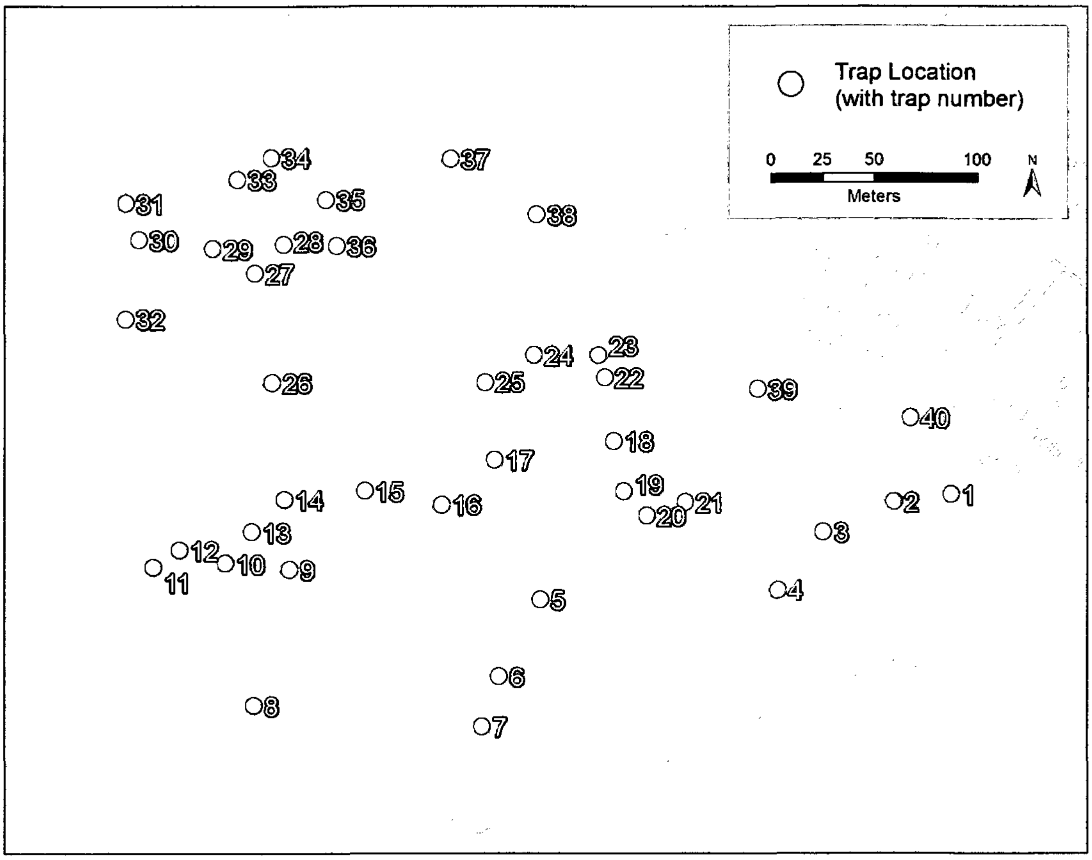


Figure 3. Random trapping locations, 2008; Warm Spring Mouse Pasture, Fremont, CA.

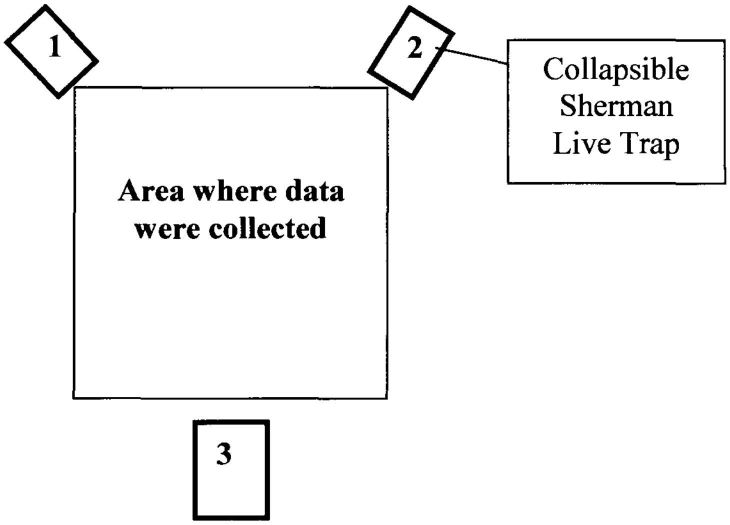


Figure 4. Example of trap placement at each sampling location.

I baited each trap with birdseed, peanut butter, and crushed walnuts and placed a small amount of food such as mealworms, jerky, or grasshoppers was provided in each trap in case of trapping a shrew (*Sorex* spp.), which is an insectivore. I placed a small amount of polyester pillow filling was placed in the trap as bedding material and to insulate the mice from cold weather. I set traps for four consecutive nights per month, for a total of 480 trap nights per month. There was one trapping occasion per month from May to August, 2008 for a total of four months and 1,920 trap nights.

I set traps in the afternoon, one hour prior to sunset, and checked them following morning before sunrise. I processed captured animals near the capture locations and released them at the location where they were trapped. I distinguished SMHM from western harvest mice using the point system developed by Shellhammer (1984) (Table 1).

I determined the sex of the animal based on the distance between the penis and anus, or urethra and anus.

Table 1. *Traits used to distinguish between salt marsh and western harvest mice*

CHARACTERISTIC	**SCORE**		
	0	**1**	**2**
Tail tip	Blunt	Intermediate	Pointed
Pattern of tail	Unicolored	Intermediate	Bicolored
White hairs on tail	None	Few	White Hairs
Tail diameter at 20mm from body	≥ 2.1 mm	2.0 mm	≤ 1.9 mm

Total Score = 1-3 Salt Marsh Harvest Mouse (*Reithrodontomys raviventris)*
= 4-5 Unidentifiable (*Reithrodontomys spp.)*
= 6-8 Western Harvest Mouse (*Reithrodontomys megalotis)*

Other data collected on *Reithrodontomys* species include body length, tail length, ear length, hind leg length, presence of visible parasites, reproductive status, venter coloration, weight, behavior, and presence of orange ear tufts. Data collected on all rodents, not just *Reithrodontomys* species, include weight, sex, reproductive status, and presence of parasites. *Reithrodontomys* species were fitted with an ear-tag with a unique identification number manufactured by National Band and Tag Co. I followed standard live mark-recapture techniques and animal handling methods (Animal Care and Use Committee, 1998). I obtained approval from the Institutional Animal Care and Use Committee at San Jose State University (#906). I am currently listed on the USFWS permit to handle SMHM (Permit TE-702631, Subpermit SFBNWR-19).

Since SMHM are an endangered species I took extra safety precautions to minimize their risk. I closed each trap immediately after checking it in the morning to ensure no animals entered the traps during the day. A minimum of two people were involved in this activity, one to check traps and another to check that the trap was shut and record data. In order to protect animals from the heat, I created shade and camouflage with pieces of wood that were placed on and around the traps. All animals were processed as quickly as possible and released immediately after processing. The ears of all *Reithrodontomys* species were swabbed with bactine prior to ear-tagging to prevent infection.

To characterize habitat quality, I collected data at each trap site on percent cover of vegetation; pickleweed height, distance to levee, distance to water, distance to bare area, and pickleweed salinity. I collected the percent cover of vegetation one week prior to the first trapping session and used GIS to determine the distance of the traps to the levee. I measured pickleweed height, pickleweed salinity, distance to water, and distance to bare area each month prior to trapping as these variables change month to month.

I used a meter long stick with 10 pins to determine the percent cover of vegetation at each site by randomly placing the pin stick three times in a meter square plot located at each site and recording the vegetation touching each pin. The number of times each species touched a pin in a plot was multiplied by 3.333 to estimate percent cover. A random sample of pickleweed was measured for height and collected for salinity analysis. Each salinity sample was bagged, labeled, and placed in an ice cooler. Samples were refrigerated and tested within two weeks of collection. To measure pickleweed salinity, a portion of the plant was pressed through a garlic press. The pickleweed sap was then placed onto a refractometer (Westover Model RHS-10ATC) and measured in parts per thousand (ppt) (Geissel et al., 1988; Kingma, 2003). Each sample was measured twice and the results were averaged.

I conducted all statistical analyses using MYSTAT or SYSTAT (SYSTAT Software, Inc., Richmond, CA) except planned comparisons, which were conducted using SPSS (SPSS Inc., Chicago, IL). I used a significance value of 0.05. Habitat differences were tested between locations where mice were present and those where mice were absent using an unpaired t-test. For values that changed monthly, I used a chi-square test of association using presence/absence data with each of the three species and grouped habitat parameters. The categories for pickleweed salinity were 62 – 75 ppt, 76 - 90 ppt, 91-105 ppt, 106-120 ppt, and 121 – 170 ppt. I grouped data for distance to dry area (0 - 5.9m and >5.9m), distance to water (0 - 5.9m and >5.9m), and pickleweed height (1 - 250mm, 251 – 400mm, and 400 – 600mm). I also grouped grass species consisting of rabbit-foot grass (*Polypogon monspeliensis*), soft brome (*Bromus hordeaceus*), salt grass (*Distichlis spicata*), Italian ryegrass (*Lolium multiflorum*), spiny sowthistle (*Sonchus apser*), barley (*Hordeum* spp.), and an unknown species, for analysis. I used an Analysis of Variance (ANOVA) to test for monthly differences in pickleweed salinity.

The mouse pasture was flooded between the June and July sampling events. In order to detect a difference in the numbers of captures at each location pre-and-post flooding I pooled capture data from May and June (pre-flooding), and July and August (post-flooding). I used a Yates chi-square test statistic, which is a small sample size adjustment to the Pearson chi-square statistic (SYSTAT Software, 2007).

I used logistic regression to test for differences in microhabitat characteristics between present and absent sites. Logistic regression evaluates the predictive efficiency of models from multiple categorical or continuous variables and one dichotomous dependent variable (presence/absence). I initially analyzed each independent variable using univariate logistic regression to determine which individual variables were most predictive of mouse presence and included parameters with p-values < 0.25 in the multivariate analysis (Marriot, 2003).

I used a forward and backward stepwise logistic regression was used to determine which variables best explained small mammal presence. I ran simulations of dependent variables that are significant in the t-test or chi-square test of association to determine the predictive probability of that variable.

I used a General Linear Model to test for differences in weight using time and gender as factors, and to test for differences in mean salinity values across time using the post-hoc Bonferroni comparison. I used a chi-square test to test for differences in gender frequencies between males and females.

The mark-recapture data were analyzed using the program MARK (Program MARK, Fort Collins, CO). Closed models were run for SMHM during June and July to estimate population size, capture probability, and recapture probability (there were no recaptures in May or August). I used eight different models to estimate the size of closed populations (Otis et al., 1978), which incorporate three different sources of variation in detection probabilities: time variation (*t*); behavioral response (*b*); and individual heterogeneity (*h*). The eight models are developed using combinations of these three factors, and the null model (M_O) which has constant detection probabilities.

I assumed *Reithrodontomys* populations were closed within the four days of trapping each month, but were open (subject to birth, death, immigration, and emigration) from month to month. The model with the lowest Akaike's information criterion (AIC) value was the best fitting model. AIC model selection ranks models based on the trade-off between bias and precision of the estimates (White, 2005). In order to obtain capture and recapture probabilities, I used model averaging, which incorporates model selection uncertainty into estimates and weighs the different models (Burnham & Anderson, 1998). Closed capture models assume that all survival probabilities are 1.0 during the short time intervals of a study (for example, in this study the assumption is that animals survive within each four day sampling period), resulting in probability estimates of first capture, recapture, and number of animals in a population.

Open population models estimate survival between sampling times (May – August 2008) and recapture probabilities (White & Burnham, 1999). I used the Jolly-Seber-Cormack open model to estimate survival and capture probability for SMHM during the months of May – August. I ran different models that tested for time and gender effects. The model with the best fit is the null model, but parameter estimates were determined separately for males and females using model averaging methods. I used an open Pradel model for May – August data, which estimates a period-specific finite rate of population change, or lambda, directly from mark-recapture data (Pradel, 1996). All parameters were estimated using a weighted average of the models (Burnham & Anderson, 1998; MacKenzie, Nichols, Sutton, Kawanishi, & Bailey, 2005).

Results

Capture Results

The species I caught during this study were SMHM, western harvest mice, harvest mice that could not be identified to species (RESP), house mice, and California voles. Thirty-six individual SMHM were captured with 15 additional re-captures, 17 individual RESP were captured with 14 additional re-captures, and 9 western harvest mice were captured with 2 additional re-captures. There were a total of 27 house mice and 4 California voles, both whom were not individually marked. Only one juvenile *Reithrodontomys* was captured and I could not identify it to species. The total CPTE (number of animals caught divided by number of trap nights) was 0.019 for SMHM, 0.009 for RESP, and 0.005 for western harvest mouse. Captures for SMHM varied temporally, with low numbers in May, a peak in June, and a gradual decrease in July and August (Figure 5). RESP and western harvest mouse showed slight differences in temporal variation (Figure 6). California voles were only caught three times in May and once in June. House mice captures were high in May, peaked in June, dropped sharply in July, and increased in August.

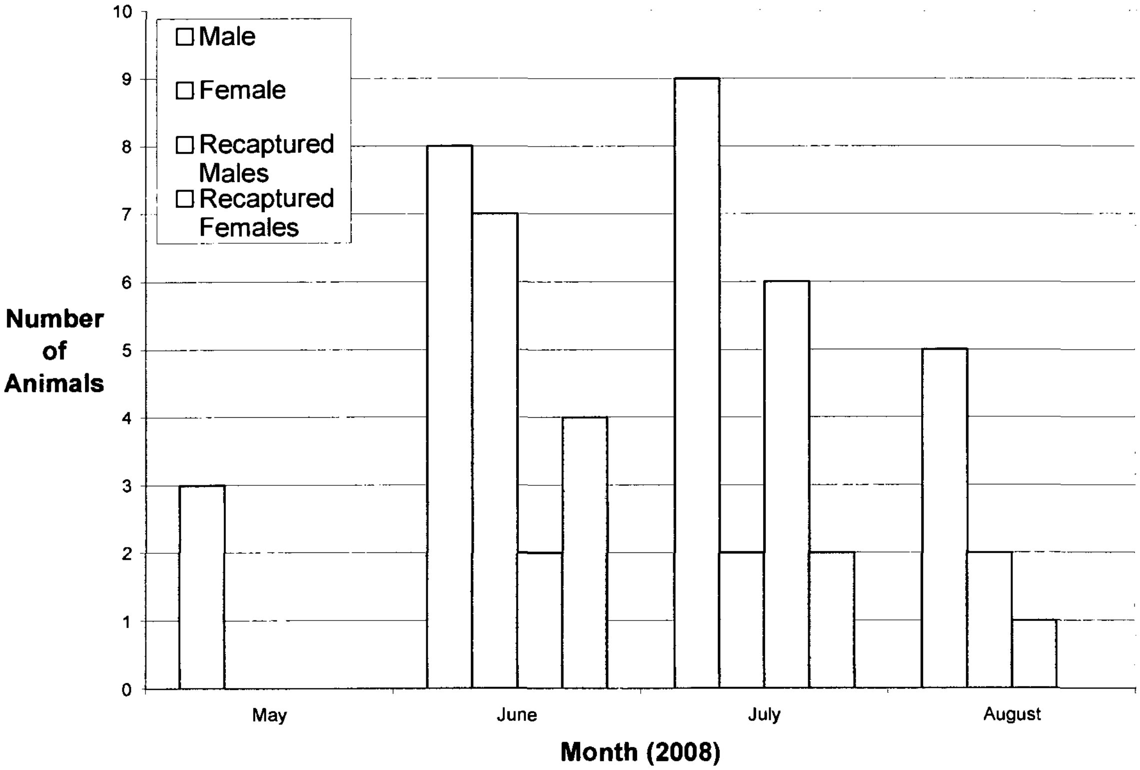


Figure 5. Number of monthly captures and recaptures of *Reithrodontomys raviventris raviventris*.

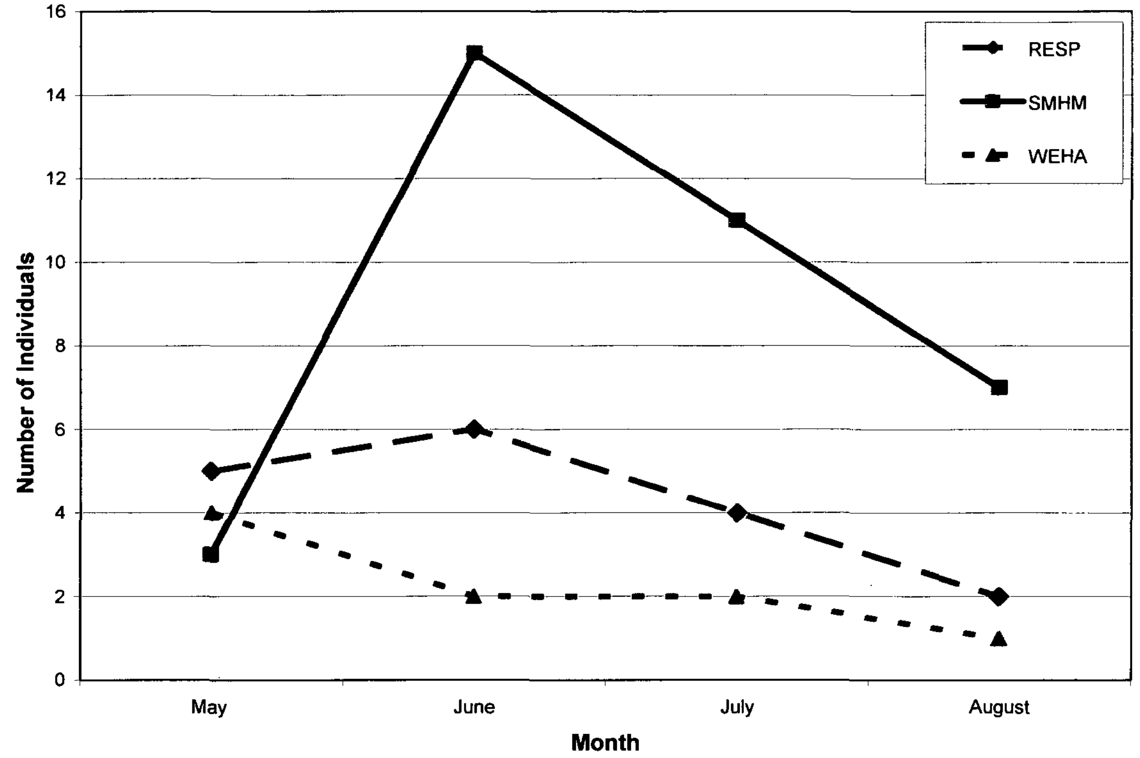


Figure 6. Number of new *Reithrodontomys* captures per month, by species. RESP = *Reithrodontomys* identified to genus only; SMHM = salt marsh harvest mice; WEHM = western harvest mice.

The sex ratio for SMHM iss skewed towards males with 25 males and 11 females ($p < 0.05$). Sex ratios for RESP (10:7) and western harvest mice (1:2) were not significantly skewed towards males or females ($p > 0.05$), but this could be attributed to a small sample size (Figure 7). Weight based on sex does not differ statistically for SMHM and RESP (SMHM $F_{(48,1)} = 0.531$, $p = 0.470$; RESP $F_{(30,1)} = 2.211$, $p = 0.151$) or month (SMHM $F_{(48,1)} = 2.293$, $p = 0.113$; RESP $F_{(30,1)} = 1.792$, $p = 0.178$). A higher proportion of reproductive individuals were caught in August than in the previous months, particularly for females. The total numbers of reproductive animals are similar across months, with the exception of May, which had no reproductive individuals, although this may be due to the small numbers of animals caught that month (Figure 8).

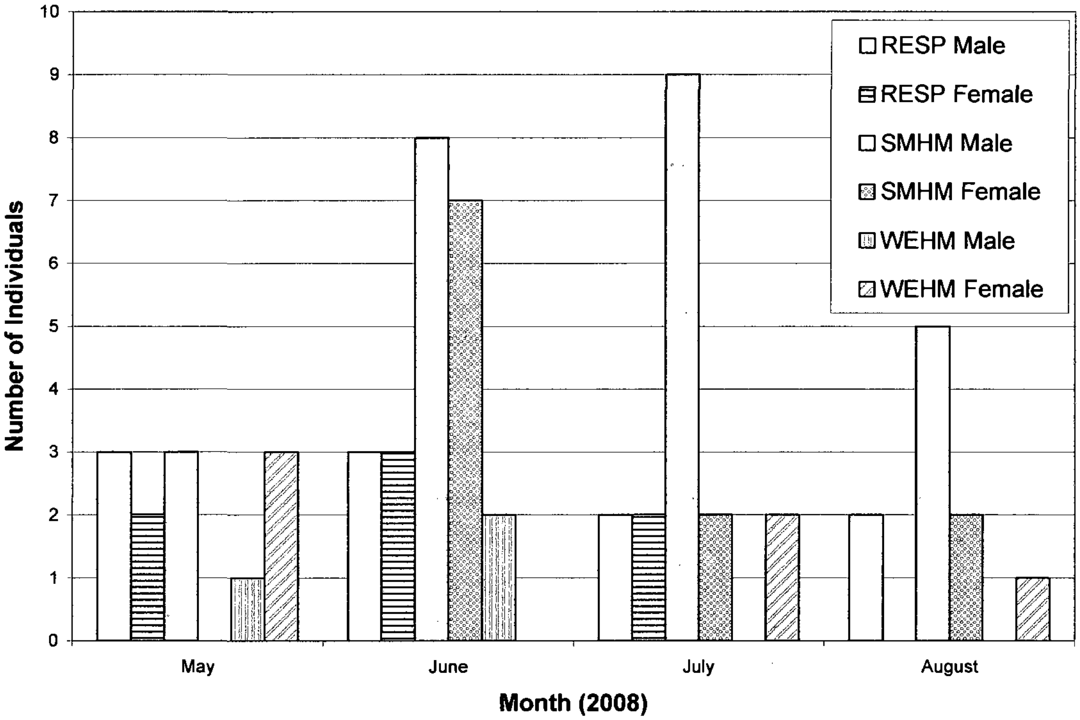


Figure 7. Number of new monthly *Reithrodontomys* captures by sex. RESP = *Reithrodontomys* identified to genus only; SMHM = salt marsh harvest mice; WEHM = western harvest mice.

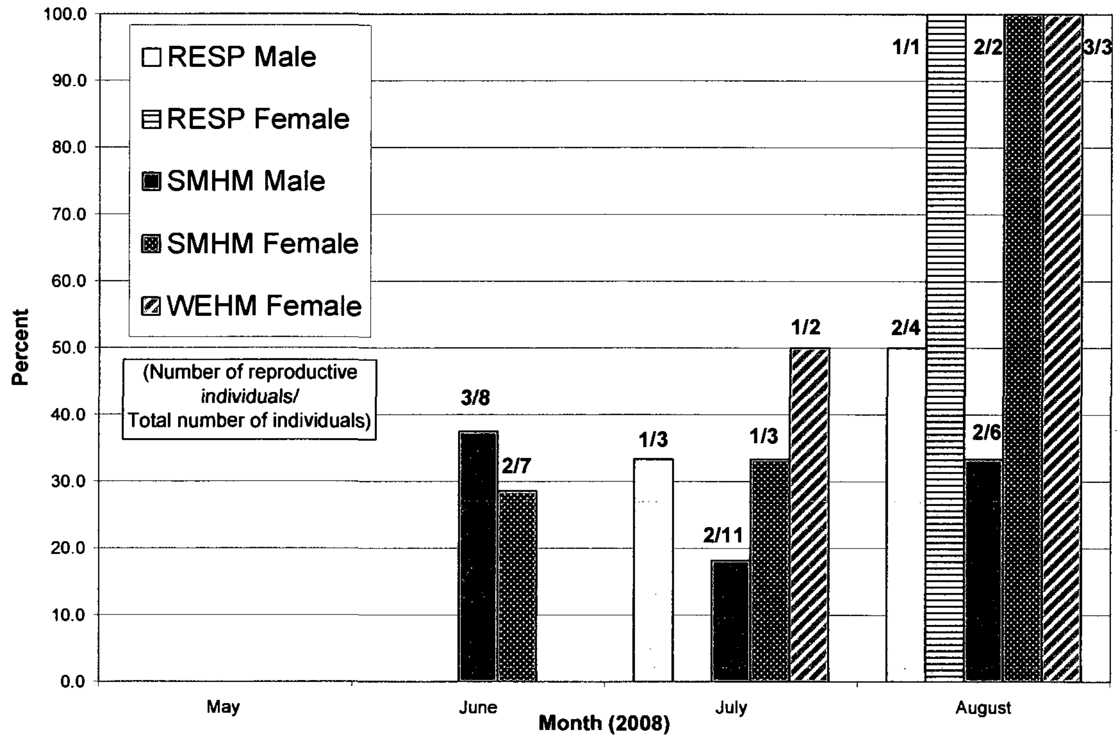


Figure 8. Proportion of reproductive *Reithrodontomys* captures by sex and month. Numbers are of new captures for the month only and may include individuals recaptured in previous months. RESP = *Reithrodontomys* identified to genus only; SMHM = salt marsh harvest mice; WEHM = western harvest mice.

The dominant plant at WSMP (n = 40) was pickleweed which was present at 100% of trap sites with an average cover of 69.8% (4.4 SE). Other cover consisted of alkali heath (16.6%, 4.0 SE), bare ground (14.3%, 2.7 SE), and grasses (12%, 3.0 SE) (Figure 9). The distance of the traps to the levee ranged from 0-127.4 meters (n = 40), with a mean distance of 51.6 m (5.7 SE). The pickleweed height ranged from 145mm to 660mm, with a mean height of 320.3mm (n = 160, 7.6 SE). The mean pickleweed salinity level varied by month $P < 0.005$; $F_{(155, 3)} = 18.7$. The mean pickleweed salinity level in May was different ($p < 0.5$) than the mean levels for June, July, and August, and the mean pickleweed salinity level for June was different (p <0.5) than the mean levels for May and August (Figure 10).

The mean values for distance of all traps to the nearest dry water body (n = 40) was 7.2 m (0.8 SE) in May, 5.9 m (0.8 SE) in June, >15.2 m (1.0 SE) in July, and 11.4 m (0.9 SE) in August. In contrast to this, the mean values for distance of all traps to the nearest filled water body (n = 40) was 14.1 m (0.5 SE) in May, >15.2 m (0.0 SE) in June, 7.5 m (0.8 SE) in July, and 10.9 m (0.9 SE) in August (Figure 11). The change in values occurred because the WSMP was flooded on July 2, 2008 as part of its water management regime.

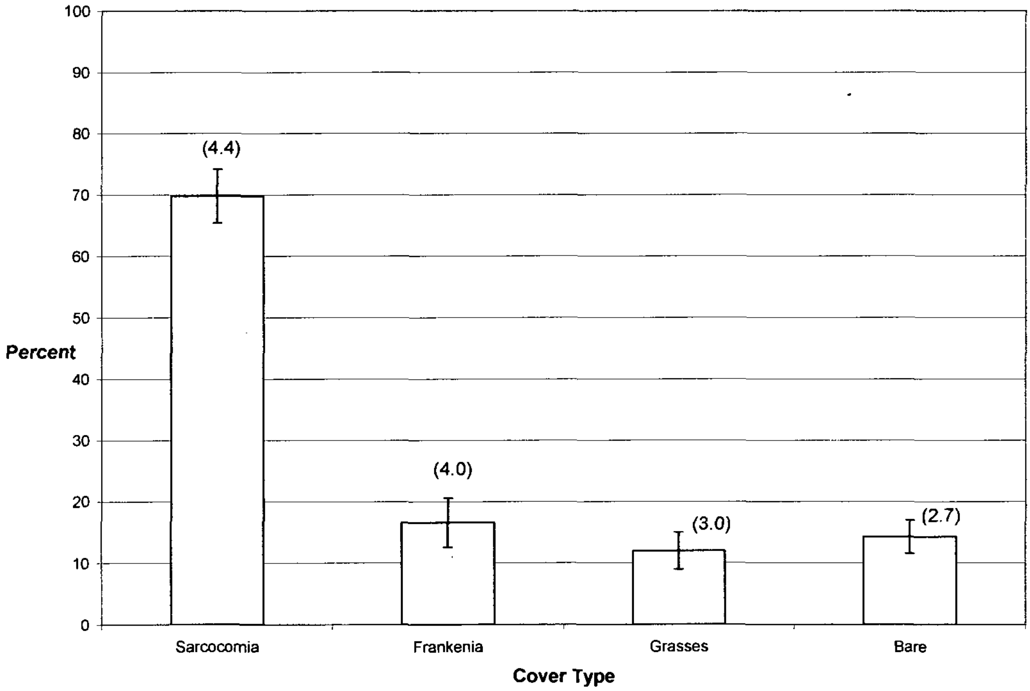


Figure 9. Percent cover of vegetation at Warm Springs Mouse Pasture. N=40. Standard error shown in parentheses.

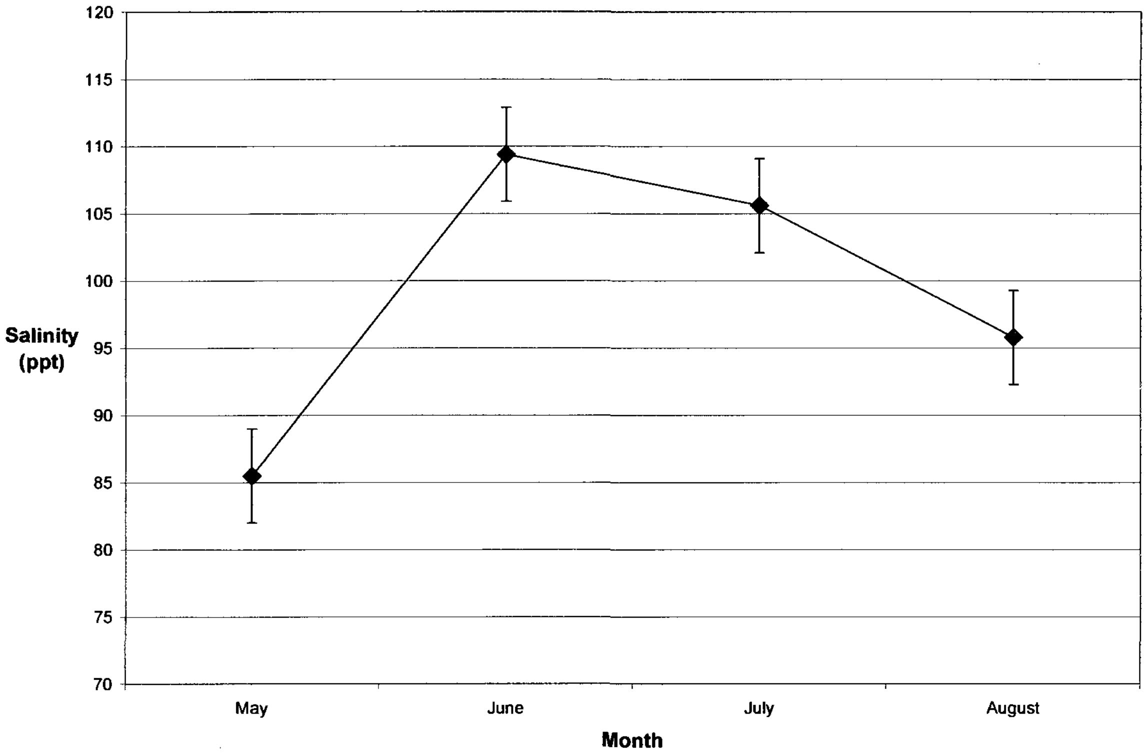


Figure 10. Mean *Sarcocornia* salinity levels per month. $P < 0.005$; $F_{(155, 3)} = 18.7$N=40, SE = 3.5

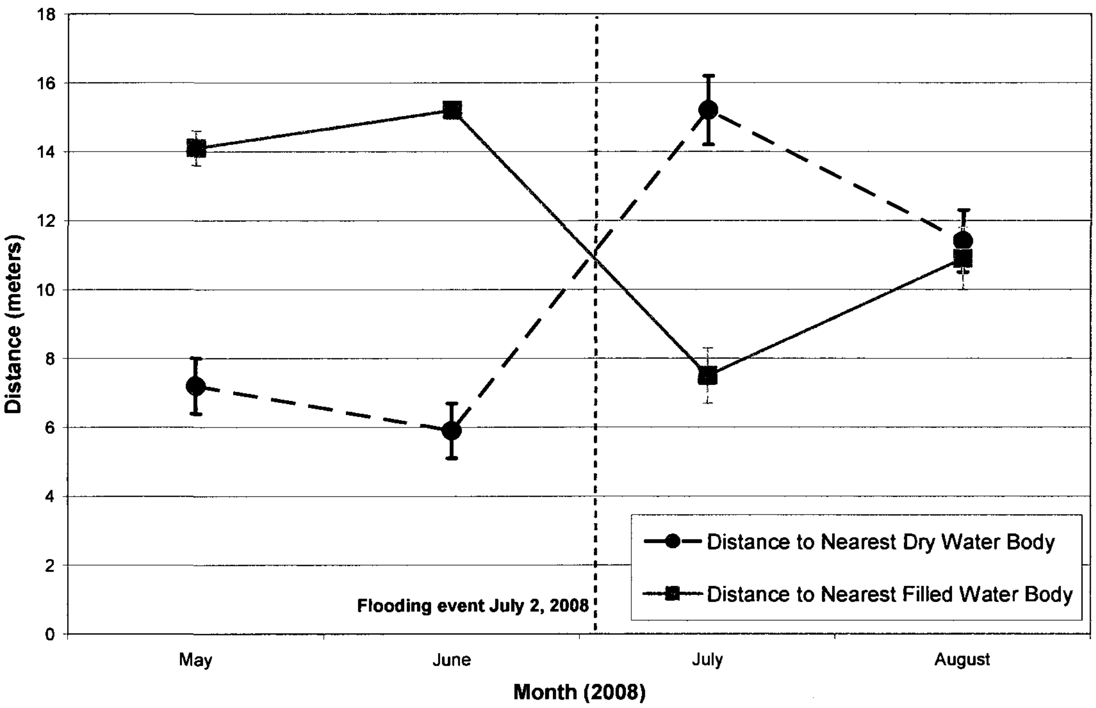


Figure 11. Mean distance of traps to dry and filled water bodies.

The majority (25) *Reithrodontomys* recaptures were trapped in the same location as the original capture site, with only 6 recaptures in different locations even when re-captured in different months. The longest distance a RESP moved was 86 meters between July and August. The second longest distance was 59 meters by a RESP caught twice in August. Two different SMHM individuals (with one moving back and forth between the traps) and 1 RESP moved between traps 2 and 3 (located near each other at 37 m). Even with recaptures in different months, the highest frequency of distance moved is 0 meters (Figure 12).

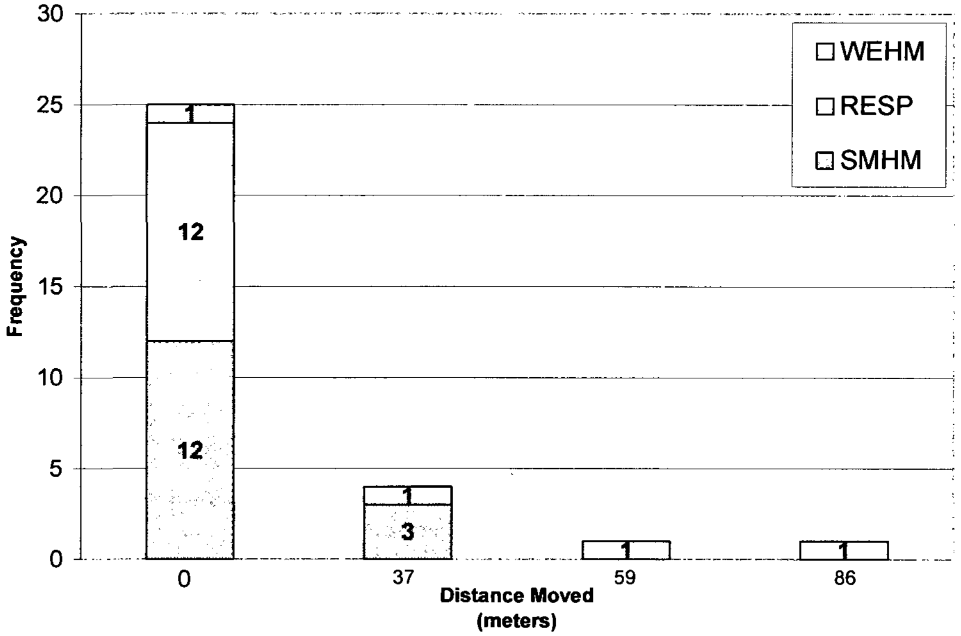


Figure 12. Distance moved of recaptured *Reithrodontomys* with number of individuals shown in bars. WEHM = western harvest mice, RESP = *Reithrodontomys* identified to genus only, SMHM = salt marsh harvest mice.

Habitat Characteristics

The habitat characteristics at locations where house mice were present versus not present differed in pickleweed cover (p = 0.028, t = 2.325, n = 40) and distance to levee (p = 0.011, t = -2.702, n = 40) (Table 1). Specifically, the mean percent cover of pickleweed was greater at 83.6% (n = 12, SD = 22.9) and the mean distance to levee was lower at 32.5 m (n = 12, SD = 24.8) in sites where house mice were present as compared to 63.9% (n = 28, SD = 28.1) and 59.7 m (n =28, SD = 37.4) at sites where house mice were absent. SMHM captures did not show differences in vegetation or physical qualities (Table 2). Sites where RESP were present had a lower percentage of alkali heath compared to sites where they were not captured. Specifically, alkali heath cover in sites where RESP were captured was 7.9% (n = 16) compared to 22.4% (n = 24) when not captured.

Table 2. *Results from unpaired t-test testing for differences in present and absent sites. House mice: n=12 present, 28 absent; SMHM: n=19 present, 21 absent; RESP: n=16 present, 24 absent.*

Species	*Sarcocornia* % Cover	*Frankenia* % Cover	Bare % Cover	Grasses % Cover	Levee Distance
House mouse	**p = 0.028** **t = 2.325**	p = 0.433 t = -0.797	p = 0.836 t = -0.210	p = 0.344 t = -0.965	**p = 0.011** **t = -2.702**
Salt marsh harvest mouse	p = 0.681 t = 0.415	p = 0.496 t = -0.688	p = 0.354 t = 0.944	p = 0.127 t =-1.560	p =0.861 t = 0.177
***Reithrodontomys* species**	p = 0.744 t = 0.330	**p = 0.038** **t = -2.166**	p = 0.335 t = 0.988	p = 0.662 t = -0.441	p = 0.875 t = -0.159

There were no statistical associations between SMHM capture sites and site parameters (Table 2), but an increase in pickleweed height (p= 0.131) approaches statistical significance. RESP presence was strongly associated with increased pickleweed height (p < 0.0005) (Table 3).

Table 3. *Results from chi-square test of associations between species and sites of presence/absence (n = 40).*

Species	Salinity	Dry Distance	Water Distance	*Sarcocornia* Height
House mouse	0.370	0.155	0.225	0.746
Salt marsh harvest mouse	0.873	0.539	0.278	0.131
***Reithrodontomys* species**	0.507	0.450	0.295	**<0.0005**

The mouse pasture was flooded in between June and July sampling events. There were no significant differences for pooled data in capture numbers pre and post-flooding for SMHM (p = 0.782), RESP (p = 0.360), or house mice (p = 0.083). Analysis using GIS showed overlap in the traps where SMHM were trapped pre- and post-flooding (Figure 13).

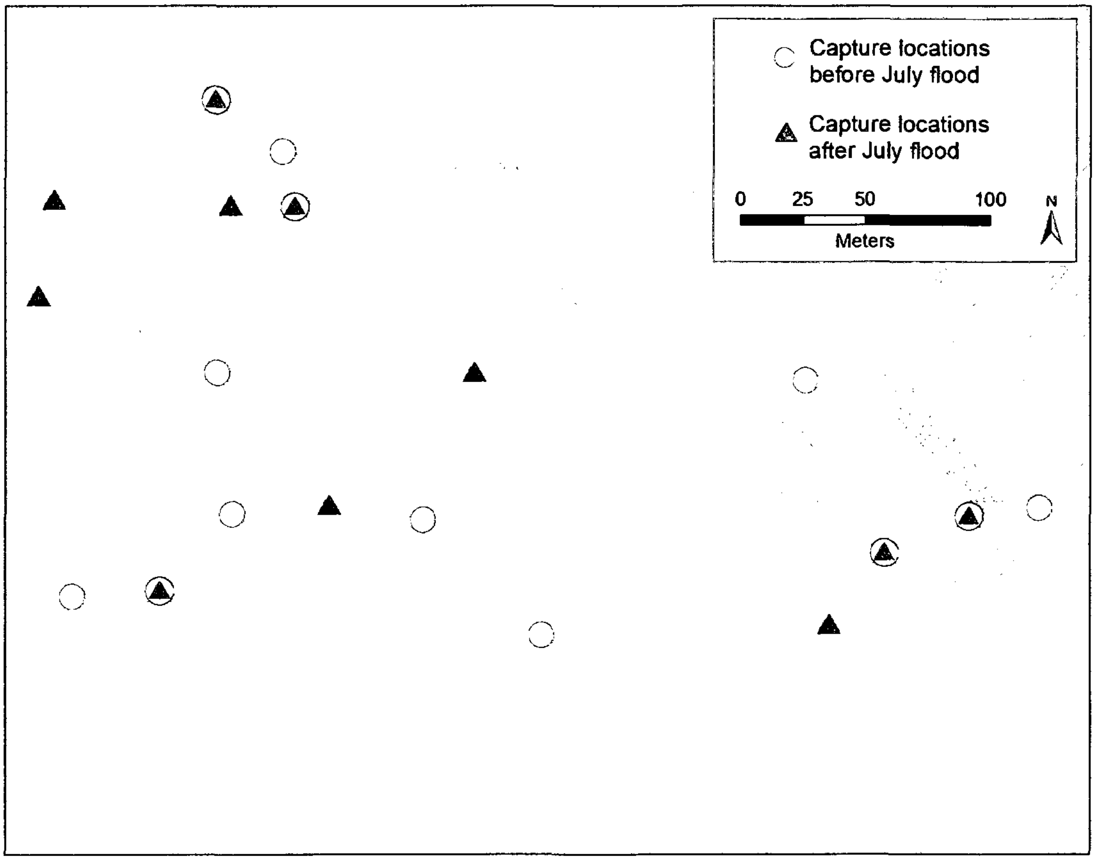


Figure 13. Overlapping capture locations of salt marsh harvest mice pre and post July 2, 2008 flooding event.

Habitat parameters most predictive of presence or absence of house mice include distance to water, distance to levee, percent cover of pickleweed grasses, and bare ground (p= 0.004). The probability of house mice presence increases as the distance to the levee decreases and as the percent cover of pickleweed increases (Table 4). The combination of characteristics most predictive of SMHM presence or absence are distance to water, pickleweed height, and percent cover of grasses and bare ground, although this model is not statistically significant (p= 0.104). For RESP, the combination of characteristics most predictive of presence or absence was pickleweed height and percent cover of alkali heath (p= 0.042), the two parameters found to be significant in an unpaired t-test and chi-square test of association (Tables 2 and 3). The probability of RESP presence increases as pickleweed height increases, but the probability of RESP presence decreases as percent cover of alkali heath increases (Table 4). The probability of house mice presence increases 29.2% as pickleweed cover increases from 0% to 100%, and decreases 4.1% as the distance to levee decreases from 125 meters to 0 meters. The probability of RESP presence increases 16.2% as alkali heath cover decreases from 100% to 0% and increases 32.7% as pickleweed height increases from 150mm to 650mm.

Table 4. *Probabilities from simulations.*

House Mice Probability (%)	**Pickleweed *(Sarcocornia)* % Cover**	**House Mice Probability (%)**	**Distance to Levee**
5	0	5	0
7.7	20	3.5	25
11.6	40	2.5	50
17.2	60	1.8	75
24.7	80	1.2	100
34.2	100	0.9	125
RESP Probability (%)	**Alkali Heath (*Frankenia*) % Cover**	**RESP Probability (%)**	**Pickleweed (*Sarcocornia*) Height (mm)**
18.3	0	10.1	150
12.3	20	14.1	250
8.1	40	19.3	350
5.2	60	25.9	450
3.3	80	33.9	550
2.1	100	42.8	650

Salt Marsh Harvest Mouse Demographics

In June, the closed model with the best fit was M*tb*, the time and behavior model, with a capture probability of 0.37 and recapture probability of 0.18. In July, the model with the best fit was M_O, the null model with a capture probability of 0.21 and a recapture probability of 0.23. The closed population estimate (N) for June was 18 SMHM, with a 95% confidence interval of 8 to 27. The closed population estimate for July was 22 SMHM with a 95% confidence interval of 3 to 40.

The survival parameter for males and females is 0.13. The model with the best fit for survival and capture probability was the null model, while the time model was the best fitting model for population growth, or lambda. Using model averaging methods, the population rate of change from May to June was 4.4, June to July was 0.79, and July to August was 0.75.

Discussion

Capture Data

The results of this study show that the WSMP, which is managed for SMHM, supports a population of at least 36 mice at a density of 3.6 mice per hectare. This density of mice is higher than at other nearby locations. In the New Chicago Marsh, a 142 hectare diked marsh located in Alviso, Padgett-Flohr (1999) found 0.38 mice per hectare in 1997, and USFWS found 0.03 mice per hectare in 2007 (Buffa, 2007a). Kingma (2003) found 0.43 mice per hectare, trapping in three different locations covering a total of 40 ha within Roberts Landing in San Leandro. Caution must be used when comparing results from different studies due to differences in methodologies, effort, and time.

Previous salt marsh harvest mouse trapping studies conducted by the USFWS in the WSMP in 1985, 1989, 2004, and 2006, 2007 resulted in 1, 7, 0, 3, and 25 new SMHM respectively (Buffa, 2007a). After the sampling event in 2006, 45 SMHM were relocated from a mitigation site to the WSMP, which may account for the increase in numbers in 2007. The density of SMHM during the years sampled resulted in 0.10, 0.69, 0, 0.30, and 2.48 mice per hectare, whereas the capture efficiency has changed from 0.001, 0.015, 0, 0.005, and 0.055 CPTE (Table 5). The current density and capture efficiency estimates for 2008 are 3.6 mice per hectare and 0.019 CPTE. Based on density it appears that the mice population is the highest in 2008, but capture efficiency suggests the mice population was higher in 2007. The differences between density and capture efficiencies highlight why density is not commonly used in SMHM studies and CPTE effort is.

However, both measures indicate the population in the WSMP has increased since 2004 when no mice were trapped.

Table 5. *Results from previous trapping efforts at the Warm Springs Mouse Pasture for salt marsh harvest mice.*

Year	New SMHM	Density (mice/ha)	CPTE
1985	1	0.1	0.001
1989	7	0.69	0.015
2004	0	0	0
2006	3	0.3	0.005
2007	25	2.48	0.055

Salt marsh harvest mice live approximately 9 months; that at least 36 mice lived in the mouse pasture in 2008 indicates that the mice may have replaced themselves through reproduction since the reintroduction of mice in 2006. A greater proportion of SMHM were reproductive in August and the sex ratio was skewed towards males, with a male to female ratio of 2.3:1. Trapping efforts in the WSMP in 2007 also resulted in a population skewed towards males, with a sex ratio of 1.8:1 males to females. The number of female mice in 2008 decreased in July after the flooding event, which may explain why the ratio of males to females in 2008 is greater than 2007. Hulst's research (2000) found the North Bay subspecies had a sex ratio of 0.95: 1.0 males to females in one location and a sex ratio of 0.5:1 in a different trapping location during the summer months (June – August). Padgett-Flohr (1999) found the sex ratio for SMHM was slightly skewed towards males (1.5:1) and Kingma (2003) found the sex ratio slightly skewed towards females (1:1.4). Bias' (1994) research of the northern subspecies found that sex ratios were consistently skewed towards females. More research needs to be conducted to determine if the sex ratio is even or if one gender is more likely to be caught than the other, and if there are differences between the northern and southern subspecies. This is an important distinction because equal probability of capture is an assumption of relative indices of abundance such as CPTE, which is the current method of estimating SMHM abundance.

The results of my study indicate SMHM are in breeding condition from June – August, with the highest proportion in August. These results differ from Padgett-Flohr (1999) who divided her study periods into three phases: pre-breeding (April – May) breeding (June – July) and post-breeding (August – September). Fisler (1965) found most SMHM (southern subspecies) males to be sexually active during the months of April through September, with the highest percentage in July. Fisler (1965) determined the female breeding season is March through November.

The closed population model results from June indicate that SMHM may have a behavioral and temporal response to trapping. This behavior is in contrast to western harvest mouse behavior. Hammond and Anthony's (2006) analysis of 12 capture-recapture data sets resulted in a capture probability of 0.34 for western harvest mouse and found heterogeneity to be a significant effect on capture probabilities with 0% of data sets showing western harvest mouse having a shy response. Males and females had equal probability of capture in their study, which is similar to the results of Bias' (1994) results.

More research on trap behavior should be conducted as this is a very important trait that can affect whether population estimates are biased. Without estimating detection probabilities, it is impossible to tell whether a change in the number of individuals surveyed at different points in time or space is due to a change in population size or in detection probability (MacKenzie & Kendall, 2002).

The number of individual SMHM changes in varies by time, with low numbers in May, a peak in June, and a gradual decline in July and August. In addition, almost all of the animals caught each month not been caught in previous months. The possible explanations for this pattern are that the animals lost their tags, are trap shy, emigrated, died, or a combination of these factors. The temporal variation in this study is similar to the peak number of captures in June found by Padgett-Flohr (1999). Six animals during my study appeared to have ear notches which may have been due to lost tags. This problem might be alleviated in the future by ear-tagging both ears. My demographic data indicate SMHM may have trap-shy behavior. However, I recaptured more animals within the same month than in subsequent months, which mean trap-shyness cannot be the only explanation. In order to truly know the answer to why mostly new animals are caught in different months, the animals should be radio-collared to determine if they are emigrating, dying, or avoiding the traps.

In the one radio-collar study of SMHM conducted with the northern subspecies, Bias and Morrison (1999) found that the mean distance moved in a 2 hour period was 11.9 m and the mean area of home ranges was 2132 m^2. The same study found that SMHM moved the greatest mean distances and had the largest home ranges during June.

The SMHM recaptures in my study show that recaptured animals were caught in similar locations as initial captures, with little movement, even if recaptured in different months. Thus, non-emigrating *Reithrodontomys* species tend to stay localized in one area. The mean maximum distance moved for western harvest mouse is <20m, which is also a relatively short distance (Hammond & Anthony, 2006).

Habitat Characteristics

Habitat quality and level of competition are both key factors in SMHM population health. At the WSMP the vegetation was dominated by pickleweed cover (69.8%), followed by alkali heath (16.6%), which are both indicators of high quality mouse habitat (Shellhammer et al., 1982). The WSMP pickleweed salinity levels ranged from 62 ppt to 170 ppt. There is no association between capture location and pickleweed salinity level in this study. Previous research on salinity levels conflict with each other and with the results of this study. For example, Zetterquist (1977) found SMHM preferred high levels of water and pickleweed salinity (the pickleweed salinity level is not published), whereas Padgett-Flohr and Isakson (2003) found SMHM were associated with pickleweed in a mid-range salinity level of (500-699 mmol/kg Cl^-), were rare in hyper-saline areas (699 mmol/kg Cl^-), and were not found at all in areas of low salinity (200-499 mmol/kg Cl^-). Kingman (2003) found SMHM present in areas of low and moderate range of salinity (65 -85 ppt) and absent in areas of high pickleweed salinity. However, Zetterquist's research was conducted in marginal habitats and the mice may have been using suboptimal conditions because higher quality habitat was not available. Pickleweed salinity research has been conducted under different temporal and habitat conditions, with different ranges of pickleweed salinity levels at each site. These differing conditions may be why no pattern of pickleweed salinity level with respect to SMHM habitat use has emerged in previous research.

The WSMP lacks areas for high tide refugia, which are an important component of SMHM habitat (Shellhammer et al., 1982). However, the WSMP is a muted marsh that is not subject to tidal action. Water inundation is an important factor in maintaining habitat quality (Buffa, 2004), but changes in water level in early July during this study may have had negative effects on the population. In particular, the number of females caught decreased from seven in June to two in July (while the number of males increased from eight in June to nine in July). The decline in captured females might be due to behavioral changes during the breeding season. In the absence of a cause-and-effect explanation and because the mice do not have refugia for water inundation that protects them from predation, it is important to limit the inundation of water levels to a level where mice can find refugia in taller stands of pickleweed.

The specific objectives listed in the 2004 WSMP Water Management Plan are to increase SMHM capture rate by 1.5 mice per 100 trap nights by 2008, increase pickleweed cover to 75-80% by 2012, increase the average height of pickleweed cover to 300 mm by 2012, reduce non-native plant cover to <5% by 2008, manage water during the growing season of May – Oct. to approximate high tide cycle, and maintain pickleweed in a green and vigorous condition. At the WSMP in 2007, the SMHM capture rate was high at 5.6 mice per 100 trap nights, and in 2008 the capture rate was 1.9 mice per 100 trap nights, indicating that the SMHM capture rate management objective has been met. In 2008, the average pickleweed cover was 69.8% and 320.3 mm, indicating that the pickleweed height objectives have been met and the pickleweed cover conditions are nearly met. Grasses, most of which are non-native, make up 12% of the cover; a reduction of 7% in grasses is still needed to meet the objectives of the WSMP. Areas of the WSMP appeared dry in July prior to flooding, but overall pickleweed appeared to be in a green and vigorous condition.

SMHM appear to be randomly distributed throughout the marsh, with no significant difference in distribution based on cover, pickleweed height, distance to levee, and distance to water bodies (dry or filled), although it is possible they avoid areas that have grasses and bare ground. Pickleweed height was significant for RESP, and of interest to SMHM, which supports previous research findings that SMHM prefer pickleweed height of 450-750mm in height (Wondolleck et al. 1976) and that the value of pickleweed increases with depth (Shellhammer et al. 1982).

Sympatric Rodent Species

Sympatric rodent species typically found in SMHM habitat are California voles, house mice, western harvest mice, and the Salt Marsh Wandering Shrew (*Sorex vagrans haliocoetes*) (Goals Project, 2000). At the WSMP, I captured four California voles, 27 house mice, and nine new western harvest mice. House mice, the sympatric species I trapped most commonly, were mostly found in areas with high pickleweed cover and near levees. Although house mice were found in areas near levees, there was considerable overlap between SMHM and house mice habitat. Of the 21 locations where SMHM was found, house mice were trapped in eight of those (38%), indicating their habitats overlap and that SMHM also use edge habitat, although not exclusively. It is possible that house mice outcompete SMHM because they are larger, but it is more likely that both SMHM and house mice face competition pressure from California voles as voles are larger, more aggressive, and superior competitors to house mice and western harvest mice (Blaustein, 1980). Voles tend to go through population cycles that reach a peak every three or four years (Krebs & Myers, 1974). There were four California vole total captures (animals were not marked) in 2008, six individuals in 2007, and 38 individuals in 2006. In contrast, there were 36 SMHM individuals trapped in 2008, 27 in 2007, and three in 2006. The low number of SMHM in 2006 may have been due to the relatively high number of California voles. Salt marsh harvest mouse numbers in 2007 and 2008 may have increased as California vole numbers decreased. Blaustein's (1980) work in a California grassland indicates that western harvest mice and house mice may coexist with California voles as fugitive species by persisting in areas where California voles cannot exist. California voles are not as good swimmers as SMHM, are poorly adapted to conserve water, and are not specialized to tolerate high saline environments (Fisler, 1965). Geissel et al. (1988) found that SMHM appear to be a fugitive species, using poorer quality pickleweed habitat when California voles are numerous, and moving into better quality vegetation when the California vole population crashes. Bias and Morrison (2006) found California vole habitat use to be negatively associated with water cover and depth and suggest that restoring tidal action may reduce competition with voles. They found positive associations between voles and all other habitat measurements (shrub, pickleweed, litter, $\leq$1-cm diameter woody debris cover, foliage height densities, and mean vegetation height), suggesting that voles are able to tolerate different vegetative conditions, but not water conditions. SMHM may exist as refugia species, occupying space with water cover when vole numbers are high. High salinity values may also act as refuge areas for SMHM. Zetterquist (1977) found the highest densities of SMHM in marginal habitats where the salinity was the highest.

Abundance Estimation

The survival parameter, or the probability that a member of the population survives between capture occasions, is based on the assumption of an open population. An open population, as opposed to a closed population, assumes that there are births, deaths, immigration, and emigration. The results of this study show a low survival parameter at 0.13. Possible explanations for the low survival rate are that animals are emigrating or dying. I trapped only adults (juveniles were too light to set off the traps), and my research does not factor in the recruitment rate, which may in fact be replacing the population. Salt marsh harvest mice are also short lived with a life span of approximately 9 months. If animals are dying, it is possible that these deaths are occurring at the end of their life cycle. More research is needed to determine SMHM survival rates and the factors affecting it.

The lambda value for SMHM from May to June was 4.4, June to July was 0.79, and July to August was 0.75, indicating that the population increased between May and June and decreased from June to August. These results are from data gathered over a very short time-frame, and results cannot be interpreted to mean the population is increasing or decreasing. The population growth rate during this study could also be affected by many different factors. An important concern in understanding and managing animal populations is the estimate of population trends over time and the factors that may affect the variation in population growth rates (Franklin, 2001). This type of research for SMHM was piloted during this study. If this research was expanded to include multi-year data, it could provide very useful data on survival and the population rate of change which has important management implications.

Estimating animal abundance of vertebrate species or populations is critical to assessing their status (D. K. Rosenberg, Overton, & Anthony, 1995). Indices, which use count data, are useful for estimating population changes when absolute estimates are not available (Seber, 1992). In contrast to indices, estimates of population size involve estimating probability of capture and using this information to extrapolate to total population size (Slade & Blair, 2000). Catch per unit effort is an index often used to estimate SMHM population size (Shellhammer & Padgett-Flohr, 2002), and it makes the assumption of equal probability of capture. Correcting the index M_{t+1} according to effort is not recommended, as catch per unit effort assumes a linear relationship between capture and effort that is unsubstantiated (McKelvey & Pearson, 2001). Therefore, using CPTE as a method of estimating SMHM abundance should be discontinued.

It is nearly impossible to trap all animals in a given area in a closed population; therefore data are collected for the index number of unique individuals captured (M_{t+1}) (Otis et al., 1978). This index is generally negatively biased because M_{t+1} will always be less than the true population size N. To convert M_{t+1} into N, various functions based on capture-recapture data analysis are used to examine the underlying sources of variation in capture probabilities to define and control the conversion (McKelvey & Pearson, 2001). McKelvey and Pearson (2001) found M_{t+1} to be the metric most robust to changes in the underlying population. My research suggests that the index assumption of equal probability of capture is not valid for SMHM based on the time and behavior effects found in June. The effectiveness of M_{t+1}, and model estimation for SMHM should be examined and tested experimentally by sampling an enclosed population with a known number of individuals under a variety of conditions and comparing different estimation methodologies with the true population size (Seber, 1992). In the meantime, M_{t+1} should be used to estimate SMHM populations, not CPTE.

Historically, the majority of mammalian studies have used count data and this tendency continues (Slade & Blair, 2000). Researchers choose indices based on counts as opposed to mark-recapture models for a variety of reasons, including sampling limitations resulting in sample sizes that are too small for reliable selection among models (McKelvey & Pearson, 2001). In addition, many researchers make relative comparisons, where accuracy is less important than precision (McKelvey & Pearson, 2001). Increasing trapping periods may also be cost prohibitive and may increase animal trap mortality (D.K. Rosenberg & Anthony, 1993), a concern when dealing with an endangered species. By definition, endangered species sample sizes tend to be small, making sampling difficult (MacKenzie et al., 2005).

Modern methods with new software and estimators allow combining data across multiple studies and/or sites to provide more reliable model selection and parameter estimation (White, 2005). In addition, new methods are available to deal with the challenges of using mark-and-recapture models. MacKenzie et al. (2005) provide two methods for dealing with population studies of rare species. The first is borrowing information about detectability or other parameters from other times, places, or species. The second is to use other variables such as species richness and occupancy. Regardless of whether the method is counts, counts using mark-recapture, or model estimation using mark-recapture data, the assumption of equal probability of capture must either be verified (White, 2005) or factored into model selection (White & Burnham, 1999).

Recommendations

The results of this study lead to a number of management recommendations.

1. *Continue current management practices of the WSMP Water Management Plan and flood the site at least four times during the growing season.*

Salt marsh harvest mice are utilizing all areas of the WSMP and population numbers have increased since implementation of the WSMP Water Management Plan. Ensure that flooding is done to keep pickleweed in a green and vigorous condition and that it does not completely inundate areas causing mice to use the levees for refugia.

Previous research indicates that California vole are superior competitors to SMHM, particularly during a population eruption (Blaustein, 1980; Heske, Ostfeld, & Lidicker, 1984), and that they are not well adapted to water (Fisler, 1965). Bias and Morrison (2006) recommend restoring tidal action to reduce competition with California vole. The WSMP is a diked marsh, however frequent flooding may also have the effect of reducing competition with California voles. Previous trapping results at WSMP in 2006, 2007, and 2008 indicate that when California vole density was high, SMHM density was low, and vice versa. This may be coincidental, particularly since 45 SMHM were relocated to the WSMP between the 2006 and 2007 sampling events. Future sampling efforts may determine if this inverse relationship is truly the case.

2. *Develop safe high-water refugia.*

Previous research has shown that safe high-water refugia is an important component of SMHM habitat (Shellhammer et al., 1982). The decline in females after the flooding event in July may be attributed to the flooding event and it is best to be cautious and provide refugia in order to minimize potential disturbances. One method to develop high tide refugia is to plant marsh gumplant (*Grindelia* sp.) in areas of the WSMP (Hulst, 2000).

3. *Continue monitoring efforts to ensure the management objectives of the Warm Springs Mouse Pasture Water Management Plan continue to be met.*

Monitoring efforts should focus on pickleweed cover and height and non-native annual grass cover.

4. *Conduct SMHM sampling efforts every three years for at least four months between May – September.*

The sampling effort should capture the temporal variability in SMHM captures and should therefore encompass May – September. Sampling creates paths in the habitat and potentially degrades habitat; therefore sampling should be conducted every three years. Sampling efforts should include the month of June based on the results of this study and previous research (Bias & Morrison, 1999; Padgett-Flohr & Isakson, 2003) which found higher SMHM activity during June. Sampling efforts should include a minimum of 4 nights, but ideally be longer. Increasing the sampling effort from 4 to 10 nights for a 20% probability of detection increases the percent of population trapped from 59 to 89% respectively (McKelvey & Pearson, 2001). Field and simulation studies have shown that less than 12 nights is inadequate to provide abundance estimates that have low bias and high precision (D. K. Rosenberg et al., 1995). However, 12 nights may be cost prohibitive, may increase SMHM mortality, and may violate the assumption of a closed population. Therefore, researchers should increase the number of individuals captured and recaptured by increasing the number of traps per site and using larger grid sizes (if applicable) (D. K. Rosenberg et al., 1995). If trapping will be conducted over a longer time interval, marking individuals with two ear tags is recommended. This will increase the reliability of the recapture analysis. It may also help estimate ear tag loss (Seber, 1992).

5. *Continue model selection analysis for estimation of abundance and demographic data or use the index* M_{t+1}. *Discontinue use of catch per trap effort until the relationship between catch and trap effort is verified.*

Every effort should be made not only to estimate relative abundance based on an index, but surveys should also estimate detection probabilities and use the model averaging approach for estimation (Burnham & Anderson, 1998; MacKenzie et al., 2005; White, 2005).

6. Partner with a local university to continue salt marsh harvest mouse research.

There are many research questions of interest regarding SMHM. I recommend wildlife agencies continue partnering with graduate students and universities to conduct this research. I recommend a multi-year, South Bay wide research project that focuses on three areas: genetics; demography; and occupancy modeling. MacKenzie et. al (2005) summarize that occupancy has potential to be very useful for future SMHM studies as occupancy data have been recognized to be useful for abundance studies of rare species (Difenbach et al., 1994), as well as metapopulation ecology (Hanski, 1999) and geographic range (Brown, 1995; Wikle, 2003). Research in these areas would provide much needed information for the management and protection of this species. Fundamental questions that need answering are how best to identify SMHM, and the current distribution and abundance of this species. Demographic information is useful for researchers modeling population viability analysis. Genetic analysis should be used for identification of SMHM and for determining genetic variability and areas of gene flow. The combination of distribution, abundance, gene flow, and GIS habitat data will be a very important step in creating a habitat model which can identify key areas for protection, restoration, and corridor design (Biedrzycka & Konopinski, 2008). These areas of research are especially important to SMHM conservation given the vulnerability of this endemic and endangered species to sea level rise as a result of global climate change.

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