HOME RANGE AND HABITAT USE OF SANTA ROSA
ISLAND FOXES (*UROCYON LITTORALIS SANTAROSAE*)

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TITLE: Home Range and Habitat Use of Santa Rosa Island
Foxes (*Urocyon littoralis santarosae*)

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ABSTRACT

Home Range and Habitat Use of Santa Rosa Island Foxes (*Urocyon littoralis santarosae*)

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Island foxes (*Urocyon littoralis*) are currently listed as federally endangered on four of the six Channel Islands to which they are endemic. The Santa Rosa Island (SRI) population declined by 99% during the 1990's due to non-native golden eagle (*Aquila chrysaetos*) predation and is currently the lowest fox population (~280) and density (0.86 foxes/km²) of any of the Channel Islands. The goals of this study were to assess new miniaturized GPS technology and to quantify home range and habitat use of the SRI population. This is only the second use of Global Positioning System (GPS) collars on Channel Island foxes and provides essential baseline data for the recovering population. These results can be used to guide management decisions and future habitat restoration efforts after the recent removal of non-native ungulates.

In fall 2009, 14 GPS collars were deployed on male foxes on the east side of SRI. Nine collars and three remote download datasets were recovered in 2010. The collars' battery life was 40% lower than expected at an average ($\pm$ SE) of 16.5 ± 1.7 weeks but had high performance in precision and fix rate. Collars yielded an average of 347 ± 33 locations with a fix rate of $82.3\% \pm 2.1\%$ and 88% of locations categorized as high precision.

From these data, 95% minimum convex polygon (MCP) home ranges and 95% kernel density isopleth (KDI) home ranges were created. The average 95% MCP home range size was $3.39 \pm 0.59\text{km}^2$ and the area of overlap with adjacent home ranges had a median of 5.3%. The average 95% KDI home range size was $3.82 \pm 0.68\text{km}^2$ with a median overlap of 6.0%. These home range sizes are almost triple the size reported in other island fox studies, likely due to the low fox densities in the recovering SRI population.

Habitat analysis was performed using KDI home ranges and a Euclidian distance analysis (EDA) method to assess habitat selection within the study area, the home range and the core area. Results showed selection for lupine within the study area, which no previous studies have documented. There was no significant habitat selection within the home ranges or core areas. Foxes selected for valley bottom topography and for bare and grassland habitat at night. One shortcoming of EDA is that its reliance on random points for determining second order selection can lead to unused areas being identified as selected habitat. The lack of significant selection within home ranges and core areas may be attributed to small sample sizes, use of male foxes only and the timing of the study in relation to fox reproductive biology.

I recommend further investigation in the use of lupine habitat and associated resources through prey inventory studies to further assess these findings. When densities reach historic levels of 4 foxes/km², follow up studies should be conducted to reassess home range size, overlap and habitat use to determine if home range sizes have decreased and overlap has increased. Future studies should incorporate spring and summer seasons and females to determine if foxes select a particular habitat within the core area during denning and pupping periods.

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I. Ecology and Conservation of Island Foxes (*Urocyon littoralis*) on the Channel Islands, California

HISTORY AND BACKGROUND

Distribution and Historic Data

The island fox (*Urocyon littoralis*), a relative of the grey fox (*U. cinereoargenteus*), is one of the smallest North American canids and is endemic to the Channel Islands off the coast of southern California. Six of the eight Channel Islands have an individual island fox subspecies: *U. l. catalinae* – Santa Catalina Island, *U. l. clementae* – San Clemente Island, *U. l. dickeyi* – San Nicholas Island, *U. l. littoralis* – San Miguel Island, *U. l. santarosae* – Santa Rosa Island, and *U. l. santacruzae* – Santa Cruz Island (Fig. 1.1).

Molecular and archaeological evidence suggests that foxes have been on the northern islands for 10,000-16,000 years and on the southern islands for 2,200-4,300 years (Wayne et al. 1991, Moore and Collins 1995). It is hypothesized that the mainland counterpart, the grey fox, was washed out on debris rafts during the mid to late Pleistocene when sea levels were lower and the shortest distance between the mainland and the islands was about eight kilometers. The island fox is believed to pre-date Chumash Native American inhabitation by about 1,000 years. It is believed the Chumash transported the foxes among the northern islands and to the southern islands possibly for pelts used in ritual ceremonies or as semi domesticates (Collins 1982). Archaeological evidence has recently been re-analyzed and supports a later establishment of foxes on the northern islands dating from 7,000-10,000 years ago (Rick et al. 2009).

The earliest studies of island foxes documented natural history, population size and density estimates when populations were high (Table 1.1). Key investigators working in the late 1970's included L. Laughrin and P. Collins, who currently still participate in island research.

Diet and Foraging

Island foxes have a diverse diet, mostly based on availability of resources, which includes mice, insects, lizards, birds, fruits and snails along with various other items. Diet composition and proportions vary by habitat, island and season. Main components in southern island diets include beetles (Coleoptera spp.), deer mice (*Peromyscus maniculatus*), snails (*Helix aspera*), ice plant (*Carpobrotus spp.*), prickly pear cactus fruit (*Opuntia spp.*) and Jerusalem crickets (*Stenopalmatus spp.*). Main components of northern island diets also include deer mice, beetles, Jerusalem crickets, and ice plant in addition to lizards and fruits from toyon (*Heteromeles arbutifolia*) and manzanita (*Arctostaphylos spp.*). Other items not as prevalent in the diet include crustaceans, bird eggs, ungulate and sea mammal carrion (Moore and Collins 1995, State of California 2011a).

There are rare instances of island foxes eating island spotted skunks (*Spilogale gracilis amphiala*); an endemic carnivore found on Santa Rosa and Santa Cruz (Moore and Collins 1995). At low densities, there is reduced competition pressure between these two species. Island spotted skunks are strictly nocturnal carnivores while island foxes are omnivores and typically forage during dawn, dusk and night.

Activity Patterns

Peak activity periods for island foxes follow a crepuscular pattern, although there is diurnal activity as well. Compared to their mainland relative, the grey fox, the island fox exhibits much more diurnal activity, which may be a product of being an island species with few to no predators (Coonan et al. 2010). Studies by Fausett on Santa Cruz Island examined activity and movement through different seasons, sexes and age of foxes using radio telemetry collars. The highest activity levels were during winter, with daytime activity at 64%. During the summer, daytime activity levels dropped to 36.8%, which correlated with an increase in diurnal air temperature (Fausett 1982). Males had larger home ranges and increased movement during the breeding season (Dec.-Feb.), presumably because they were seeking out multiple females (Laughrin 1980, Fausett 1982).

Breeding and Reproductive Biology

Island foxes are generally considered to be socially monogamous, which is common for Canidae (Kleiman 1977). In monogamous systems, home range sizes typically are comparable between sexes with extensive home range overlap for mated pairs (Laughrin 1977, Crooks and Van Vuren 1996, Roemer et al. 2001). Adults typically stay with one mate until one dies, and then a new mate will be sought out. However, evidence of extra pair copulations has been documented. A study on Santa Cruz Island using molecular methods to establish paternity documented a 20% incidence of extra pair copulations (Roemer 1999).

Island foxes become sexually mature within one year. Females can become pregnant in the first year, but often do not succeed in rearing pups. Courtship and pair formations typically occur from December to February with breeding from February to March; gestation lasts 50-53 days. Parturition occurs from mid-April through mid-May with biparental care exhibited once the pups emerge from the den in June (Table 1.2). Litters range in size from 1-5 pups with an average of 2-3 (Moore and Collins 1995).

When pups are born, their eyesight is limited and their pelage is dark grey to black. By the end of July or beginning of August, the adult coloration with more rust color in the pelage is achieved and the pups are close to adult size. Bi-parental care increases the survival of offspring and also further supports the overlap of mated pair home ranges. Territoriality seems to be displayed only during the denning season; otherwise it is too energetically expensive (Roemer et al. 2001). It is unclear if this territoriality holds at low densities. Pups start foraging around the natal area with their parents at the beginning of the summer and dispersal begins in late September with final dispersal from the natal area by December (Laughrin 1977, Moore and Collins 1995).

Sparse data have been collected on dispersal patterns, a subject that warrants further research. Observations of dispersal patterns include the parents expanding their range away from natal area in the fall when pups become more active. Pups stay in the natal area until December, after which dispersal typically occurs. This supports increased pup survival through foraging in a familiar area (Laughrin 1977). This is believed to correlate with the fire ecology of chaparral habitats, which historically existed on most of the islands (Fausett 1982). Field observations have shown that female pups often establish territories near natal den areas while male pups often disperse farther from natal

den areas, possibly to decrease likelihood of mating with related females. Average dispersal distances recorded for Santa Cruz Island were very low (1.39km, SD=1.26) compared to grey foxes and other canids. Due to the restricted size of the islands, long range dispersal is not possible (Roemer 1999).

Habitat and Home Range

Habitats occupied by island foxes include grassland, coastal sage scrub, lupine scrub, chaparral, mixed and riparian woodland and coastal marsh areas with the types of habitats available varying by island. Typically, the southern islands have a lower diversity of habitats along with a drier climate. The larger northern islands, specifically Santa Cruz and Santa Rosa, have more diverse habitats and terrain along with more annual rainfall. Laughrin (1977) showed that shrub and woodland habitats provide more cover and tend to support higher fox densities than grassland habitats.

Crooks and Van Vuren (1996) worked at two sites on Santa Cruz Island assessing diet, home range and seasonal habitat use. Data were collected across two seasons (wet and dry). Average home range size was $0.34 \pm 0.10\text{km}^2$, which is the smallest home range size reported for any canid. At one site, foxes preferred fennel-grasslands, which had the highest availability, and avoided scrub oak and ravines (Crooks and Van Vuren 1996). These data were collected at high fox densities prior to population declines, which may not be indicative of the most productive habitat, but simply the available habitat (i.e., at high densities, some foxes may be forced into marginal habitat).

Roemer et al. (1994) worked on San Clemente, Santa Catalina, Santa Cruz and San Miguel Islands, comparing density estimates based on grid trapping data in various

habitat types. Densities ranged from 2.4 to 14.3 foxes/km² based on the habitat type and the island (Table 3). These densities were recorded prior to the major declines that occurred in the late 1990s. Additional research done by Roemer looked at home range sizes and activity patterns in different habitat types. Minimum convex polygon home range size varied from 0.15 to 0.87 km² depending on habitat type. Based on metabolic needs correlated to body size, the home range sizes were expected to be larger, but due to island effects and a predominately insectivorous diet, the estimated home range size decreased and is closer to results from Crooks and Van Vuren's studies of 0.34 km² (Roemer 1999). Activity pattern results showed a significant correlation between mortality and levels of diurnal activity, specifically with higher predation rates at the open grasslands versus in chaparral and oak woodlands (Roemer et al. 2001b).

Recent research on San Nicholas Island showed no difference in home range size between sexes but differences in home range sizes during non-reproductive and reproductive periods. Results showed an average home range size of 1.81km² during mating phase with significantly smaller home ranges, averaging 0.65km², during post-mating, pupping and non-reproductive phases (Powers 2009). The smaller home range size can likely be explained by activity being centralized around a den site during the post-mating and pupping seasons.

POPULATION DECLINES AND RECOVERY EFFORTS

Population Declines

Island fox density estimates, trap efficiency and survivorship declines were documented on the northern islands during the early 1990's. Fox populations decreased

by 90-99% in approximately five years. Initially the causes for the island fox population declines were unknown. Species endemic to islands, particularly with small populations, run a much higher risk of extinction due to system perturbations (Carlquist 1974). Threats include disease, competition from introduced species, habitat destruction, or novel predation risks.

Trap efficiency on Santa Cruz fell from 25.7% during 1993-1995 to 4.3% in 1998. Fox density estimates decreased from 7.1 foxes/km² in 1993 to 0.8 foxes/km² by 1998 (Roemer et al. 2001b). San Miguel Island had a more severe decline during 1994-1999, going from 418 individuals to 15. Previously, the highest density for all island populations was recorded here at 15.9 foxes/km². Trap efficiency went from 40% to 2% at the peak of population declines in 1999. The number of pups captured on all three grids also declined (Coonan et al. 2005). Mean survival rates during 1993 to 1994 were 0.53 for pups, 0.72 for yearlings and 0.72 for adults (Roemer 1999). Declines were also documented on Santa Rosa island, which declined from about 1,500 to 14 foxes.

To determine mortality factors and possible causes for population declines, VHF telemetry collars were used. This allowed for carcasses to be recovered and mortality causes to be investigated. The data from mortality sites and necropsy reports confirmed that predation by golden eagles (*Aquila chrysaetos*) was the primary mortality factor contributing to population declines. Of 28 fox carcasses recovered on Santa Cruz and San Miguel Islands, 24 (86%) showed signs of raptor predation. This correlates with a high number of golden eagle sightings during this period (Roemer et al. 2001b, Latta et al. 2005). The declines in the northern islands were due to a novel predation event by non-native golden eagles. In addition to foxes, non-native ungulates on the northern

islands were providing a prey base for golden eagles on the northern islands (Roemer 1999). One of the southern islands, Santa Catalina, also had a population decline that was much more rapid, going from 1,300 to 165 foxes during 1999, due to a canine distemper epidemic. This disease outbreak decimated 95% of the east side population, but due to the island's natural isthmus, individuals on the west side of the island were not affected (Timm et al. 2000).

Golden eagles were a threat that island fox populations had not previously encountered. Part of the dynamic interaction was driven by large numbers of non-native deer, elk, pigs and sheep brought out to the islands by ranching families in the mid-1800s, which provided a supplementary food base for golden eagles. The other factor was the decline in native bald eagle (*Haliaeetus leucocephalus*) populations over the past fifty years due to DDT contamination and nest failure. Nesting bald eagles had previously kept transient golden eagles from establishing territories on the islands (Sharp and Garcelon 2005, Roemer et al. 2001). In addition, bald eagles have an aquatic-based diet (Stalmaster 1987) and are not a threat to island foxes, whereas golden eagles are terrestrial predators. With bald eagles absent from the islands and abundant terrestrial prey sources available, this set the stage for golden eagles to colonize the islands. This resulted in a large shift in the island food webs and quickly put the fox population at a disadvantage as a supplemental food source for new nesting golden eagles. Island foxes alone were not enough to support golden eagle colonization previously, but as a supplement, in addition to non-native prey, this provided enough food to support nesting golden eagles and drive fox populations into drastic decline (Roemer et al. 2001).

Recovery Efforts

Due to the extreme population declines recorded on multiple islands, recommendations were made for implementation of a captive breeding program on the northern islands in order to insure population persistence and the four subspecies were listed as federally endangered (Roemer et al. 2001, Coonan 2003, United States 2004). In 2000, the island fox recovery coordination group was formed to create a recovery plan incorporating captive breeding and monitoring of wild populations to increase numbers to a sustainable level. Specific recovery objectives included establishing monitoring and management of island fox populations; supplementing the wild population with releases from captive breeding facilities; removing or decreasing mortality factors such as golden eagles; restoring natural ecosystems to the northern islands; and achieving an annual survival greater than 80% and a population of 200-300 adult foxes within ten years (Coonan 2003). A target population of twenty pairs for each subspecies was established for the captive breeding program based on demographic modeling to determine population viability and extinction risks within ten years (United States 2007b). Representatives from multiple agencies and affiliations collaborated on island fox recovery efforts, including the National Park Service for San Miguel and Santa Rosa populations, The Nature Conservancy for the Santa Cruz population, the Catalina Island Conservancy for the Santa Catalina population, the United States Navy for the San Nicholas and San Clemente populations, the Institute for Wildlife Studies for the Santa Cruz population, the Santa Barbara Zoo, Friends of the Island Fox, the United States Fish and Wildlife Service, and the California Department of Fish and Game.

By 2003, the captive breeding programs had come close to reaching the goal of

twenty pairs per population. The annual growth rate for the captive populations on Santa Rosa and San Miguel island had reached 1.2 and 1.3, respectively (Coonan et al. 2005). Captive breeding programs were carried out from 2000 to 2008 on the northern islands. Ten to twenty individuals from the captive populations were released annually to the wild (Coonan et al. 2005). Annual trapping, collection of demographic and ecological data, VHF radio telemetry monitoring and remote camera stations were used to monitor and manage the population to assess recovery success. Specific data collected included abundance, density, annual survival, mortality sources, reproduction rates and disease epidemiology (Table 1.4).

Current Status

Island fox populations are recovering with higher densities and survivorship on most islands, and some of the subspecies are on the way to being delisted (Coonan 2010). Major threats of disease introduction and golden eagle predation have been addressed through various management practices, including vaccination of wild populations for canine distemper virus and rabies, along with the establishment of sentinel populations and the creation of an epidemic response plan to respond to any potential disease outbreaks. In addition, all golden eagles have been removed from the islands and an eagle rapid response plan has been established. It will be implemented if high numbers of predation mortalities begin to occur. The biological recovery criteria for populations on San Miguel, Santa Cruz and Santa Catalina, may be met by 2013 and Santa Rosa potentially by 2017 (T. Coonan-Channel Islands National Park, pers. comm.).

Introduction of non-native species can have severe effects on any population,

specifically island populations. This unique example of complex ecosystem interactions effected by perturbations strongly supports the fragility of island systems. Often these insular populations can become “conservation reliant” (Scott et al. 2005) and long term monitoring at varying levels of intensity is essential for these populations in order to prevent future drastic declines. The recovery of island foxes has been a great success story but continued monitoring will be necessary. VHF collars and annual trapping allow for collection of data on population size, density and survival.

Santa Rosa’s slow population recovery and current low density provided an opportunity to assess home range size, overlap and habitat selection with low competition for resources. I conducted the study using newly miniaturized GPS technology, which provided a robust data set. The data collected provided further insight into population dynamics and spatial ecology, which is essential in developing management and conservation plans. Specific questions addressed included: what is the average home range size and overlap and does this vary seasonally or temporally? Also, is there selection of certain habitat types or topography within the study area; the home range; and the core area?

TABLES

Table 1.1: Pre-decline island fox data for six islands.

	SMI ¹	SRI	SCZ	SNI	SCI	SCL
Island Area	37km ²	217km ²	249km ²	58km ²	194km ²	145km ²
Population ²	163	955	984	247	979	551
Trap efficiency	43%	51% ⁴	67%	27%	3%	52%
Density ³	2.7	4.1 ⁴	7.9	1.2	0.3	4.2

1. San Miguel (SMI), Santa Rosa (SRI), Santa Cruz (SCZ), San Nicholas (SNI), Santa Catalina (SCI), San Clemente (SCL)

2. Wayne et al. 1991

3. Density values (foxes/ km²) from Moore, Collins 1995, converted miles to kilometers

4. Santa Rosa data averaged across habitat types (woodland density: 5.8/km, 0.62 trap efficiency; grassland density: 2.4/km, 0.4 trapping efficiency) Laughrin 1977

Table 1.2: Annual reproduction and activity cycle with specific activities for adult males, adult females and pups. Mating occurs Dec. 15-Jan. 31, post-mating includes 50-53 day gestation and parturition from Mar. 15-May 15.

Dec.-Mar.	Apr.-May.	Jun.-Aug.	Sept.-Oct.	Nov.-Jan.
Pair formation, Breeding (B) ¹ , Denning (F) Wide range (M)	Pups born, Small range (B)	Emerge from den, forage with adults (P), small range (B)	Dispersal (P, B) (pups may stay in natal area while adults expand range)	Establish territory (P, M), Wide range (M)

1. P=pups, M=adult male, F=adult female, B=both male and female adults
Laughrin 1977, Moore and Collins 1995, Asa et al. 2007

Table 1.3: Island fox population estimates and density ranges from 1988 to 1993

	SCZ 1993	SMI 1993	SCI 1989-1990	SCL 1988-1993
Population	1,465	340	1,340	1,000
Density (foxes/km ²)	7.0-7.3	8.9-9.6	2.4-14.3	4.0-9.5

Roemer et al. 1994

Table 1.4: Current island fox population data based on 2006 -2009 annual island fox recovery team meeting reports.

	SMI 2009	SRI 2009	SCZ 2008	SNI 2007	SCI 2008	SCL 2008
Population Estimate	256	187	736	725	784	386
Density (foxes/km ²)	6.6	0.86	N/A	8.9, 16.8, 20.4 ¹	3.5	N/A
Home Range (km ²)	N/A	N/A	0.15-0.87 ²	0.65, 1.81 ³	N/A	N/A
Annual Survival	90%	80%	96%	75%, 72% ⁴	N/A	65%, 91% ⁵
Reprod Rate(pups/female)	0.8	0.9	N/A	N/A	N/A	1.9

1. Based on 3 grids: Skyline, Redeye, Tufts

2. Data from studies done 1989-1993, most recent home range data

3. Non-mating phase, mating phase

4. Adult survival and juvenile survival

5. Based on home ranges near roads and away from roads

FIGURES

Figure 1.1: Channel Islands, California (Google Earth Imagery). Foxes occur on six of the eight islands (shown in yellow): San Miguel, Santa Rosa, Santa Cruz, Santa Catalina, San Clemente and San Nicholas.

II. Evaluating Global Positioning System Collars for use on Island Foxes (*Urocyon littoralis*)

INTRODUCTION

Use of Global Positioning System (GPS) technology has increased in wildlife studies and new advances are constantly being made yet there is still room for improvement. Advantages of GPS technology include a higher rate of data acquisition, balanced distribution of data collection throughout the diel period and less personnel time and effort required compared to traditional VHF telemetry (Beyer and Haufler 1994, Johnson 2002). Downfalls include the higher cost of GPS technology, imprecision associated with dense canopy and rugged terrain, unit weight restrictions and battery life limitations for smaller species (D'Eon et al. 2002, Cain et al. 2005, Hebblewhite and Merrill 2007, Frair et al. 2010, Blackie 2010). While GPS collars are more expensive (~5x the cost) than conventional VHF collars, the increased quantity of data and time savings cost-efficiency is far superior to VHF collars. Reported location error for GPS ranges from 10-28m whereas VHF triangulation location error ranges from 200-600m (Frair et al. 2010).

Very few companies have developed GPS units smaller than 100 grams. During our study, only one company, Telemetry Solutions (Concord, CA), made miniaturized collars suitable for island foxes. One other company, Televilt (Lindesburg, Sweden), briefly produced miniaturized GPS collars but the company discontinued manufacturing these units due to performance issues (J. King, Catalina Island Conservancy, personal communication). As a result of the limited availability of miniaturized GPS technology, very little performance testing has been conducted (Blackie 2010). Most performance

testing has been done on larger GPS units, which are not limited by battery size. The main restriction in producing smaller versions of GPS technology is the battery limitations (Cain et al. 2005, Mattisson et al. 2010). With this restriction, planning of GPS unit deployment becomes essential to guarantee data capture during a limited battery life.

There is still concern for potential bias and imprecision of GPS locations, though many studies have been done to better understand this issue, particularly relating to habitat use analyses. Studies include testing precision level of fixes, determining fix rate in varying vegetation and terrain, and species-specific differences in data acquisition. Factors found to influence fix precision and fix rate include habitat and terrain, more specifically, the amount of canopy closure, topography and programmed fix interval (Moen et al. 1996, D'Eon 2003, Hebblewhite and Merrill 2007, Frair et al. 2010). When examining GPS results, the fix attempts that are not acquired are typically in habitat types which have high canopy closure or deep canyons. This can be misinterpreted as no use or avoidance of these habitats and topography conditions when they are actually being used but data are not acquired (Frair et al. 2010). These problems can be identified by performing habitat tests prior to collar deployment to assess the study areas' level of bias. GPS can be a great tool to investigate spatial ecology of animals, as long as these limitations are kept in mind.

Island foxes (*Urocyon littoralis*), a relative of the grey fox (*Urocyon cinereoargenteus*), occur on six of the eight Channel Islands, located off the coast of southern California. Sudden declines in the populations occurred on the northern islands during the 1990s. The population on San Miguel island decreased from nearly 450 to 15

island foxes; the Santa Rosa island population declined from about 1,500 to 14; the Santa Cruz island population decreased from about 1,500 to 135 (Coonan et al. 2005b, Roemer 1999). Declines were due to predation by non-native golden eagles (*Aquila chrysaetos*), which can be linked to the non-native ungulate prey base on the northern islands (Roemer 1999). Subspecies on four of the islands were listed as federally endangered in 2004 and a recovery program with captive breeding was established to prevent further declines from 2000-2008 (United States 2004, Coonan et al. 2010). Through annual trapping, collection of demographic and ecological data, and VHF radio telemetry monitoring, recovery criteria are monitored.

The recovering population on Santa Rosa island provides an excellent opportunity to look at more detailed aspects of spatial ecology such as home range size and habitat use at low density. All previous island fox data collection has been based on observations, trapping and VHF radio telemetry. This type of study is more conducive to GPS data versus VHF data due to the quantity of data collected to create accurate home ranges. Also, GPS technology allows for programming that collects accurate locations all hours of the day, independent of weather conditions or personnel limitations, giving an unbiased view of habitat utilization (Beyer and Haufler 1994). Using this newly miniaturized GPS collar technology on island foxes can serve two purposes. First, the technology can be assessed for overall functioning and its safety for use on smaller study organisms. Limited testing has been conducted on GPS collars with a reduced size and weight, and improvements are still being made with feedback from current applications. Second, it can be used to determine the level and quality of data that are collected by the GPS collars and the suitability for use of the data in habitat analysis. This data can

further improve these products and future use of this technology in wildlife research and will be of benefit both to the research community and to management agencies.

The specific GPS collar testing objectives addressed during this project were to: 1.) assess overall durability, performance and safe deployment of GPS collars on island foxes; 2.) test functioning and ease of use of the software program, Collar SW (Telemetry Solutions); 3.) determine if different habitat types affect GPS collar performance and precision through stationary tests; 4.) assess VHF functioning (frequency drift, signal strength output, pulse rate, mortality sensor functioning, battery operation time); 5.) assess GPS functioning (remote download capability, battery operation time, time to fix, horizontal dilution of precision values, fix rate overall and within different habitat types). The GPS data was also used to determine home range size, overlap and assess habitat selection within home ranges and the study area (Chap. 3).

METHODS

Study Area

We conducted our study on Santa Rosa Island (33° 57' N, 120° 05' W), California, USA. Santa Rosa is one of the northern Channel Islands that are part of Channel Islands National Park. It is the second largest (217 km²) of the eight California Channel Islands (Fig. 1.1). It is characterized by a Mediterranean climate with a marine influence. Topography of the island includes a central ridge with multiple canyons radiating out from the center of the island towards the coastline. Maximum elevation is 484 m. Habitat types include coastal grassland, island chaparral, scrub oak woodland,

coastal sage scrub, coastal bluff scrub, riparian woodland, Torrey pine forest and bishop pine forest (Schoenherr et al. 1999). The study site encompasses the eastern half of the island with a total area of 72.7 km².

GPS Collar Specifications

The Telemetry Solutions collars (Quantum 4000E mini) were equipped with a store-on-board GPS unit, a VHF unit and a mortality sensor for a total weight of 65g (Fig. 2.1). Telemetry Solutions was the only manufacturer of GPS collars that met size and weight requirements of 4% or less of body weight sufficient for deployment on island foxes. Data collected and stored on the collar included date, time, time to acquire a GPS fix (TTF), location coordinates, maximum signal-to-noise ratio (maxsnr), horizontal dilution of precision (HDOP), number of satellites, type of fix (2-dimensional or 3-dimensional), voltage and air temperature. A “fix” is equal to a location on the animal. An additional feature available was remote download capability, which allows for data retrieval within 300m of the animal using a base station connected to a laptop and yagi antenna.

The GPS units are programmable by the user with company supplied software and a USB cable connection. Two program options include a repeat mode or a calendar mode. With repeat mode, fixes attempts are made at repeated time intervals (e.g.- every 2 hours), which can be specified in programming. With calendar mode, specific daily templates can be made, each with their own specified time intervals for fixes. Multiple different templates can be made and programmed on different days for a more specialized data collection pattern. Additional setting options include three choices for time to

acquire a fix (TTF): 60 seconds, 90 seconds and 120 seconds. Also, there is an additional time feature that allows the unit to remain on if a fix is not acquired in the allotted time, programmable from 5 seconds to 120 seconds.

Stationary Pre-Deployment Collar and Software Testing

For stationary pre-deployment testing, collars were placed approximately 25 centimeters off the ground and oriented as they would be when deployed on foxes. I programmed collars for short testing periods of one to three hours. The collars were programmed to collect 5-15 fixes with five and fifteen minute intervals between fixes. Both 60 second and 90 second time to acquire a fix (TTF) were programmed with the additional fix time set at 15 seconds. A set of reference points were collected (Trimble GeoXT, sub meter accuracy) and averaged for each test. Data were then either remotely downloaded or collars were retrieved and data were downloaded via a USB cable. These pre-deployment tests were used to determine functionality of software programming features and to check data acquisition of collars.

Vegetation density can potentially bias fix rate due to canopy cover and low satellite coverage which results in missed fixes and a decreased fix rate (“fix rate” is the proportion of successful fixes out of the total fix attempts). In addition, if a fix is acquired in these conditions, often the precision of the fix is decreased (Moen et al. 1996, D’eon 2003). To assess the effects of different habitat types and potential bias on fix rate and fix precision, tests were performed in three main habitat types; grassland, scrub and woodland. Tests were performed in all three habitat types within the same day to assure similar satellite configurations when comparing results. Some tests were performed in

only two habitat types in one day. A total of 16 tests were performed: 5 in grassland, 7 in coastal scrub and 4 in woodland. These results were used to determine if our habitat analysis accurately represented habitat use based on acquired GPS data.

HDOP value, TTF, fix rate and fix type (2D or 3D) are typically good indicators of bias and can vary within different habitat types and terrain. These parameters can be dependent on satellite configuration, number of available satellites, canopy cover potentially impeding GPS signal transmission and other topographic or landscape features. Tests have shown 2D fixes to be less precise than 3D fixes and fix type is often used to filter locations. Low HDOP values typically indicate higher precision whereas high HDOP values indicate low precision based on satellite configuration (Frair et al. 2010, Moen et al. 1996).

I downloaded the data from the collars and entered it into GIS software along with post-processed Trimble reference point data. Point Distance and Join tools were used to calculate distance from the reference point to all GPS fix locations. The term “fix measurement error” will be used to address the error distance calculated from the reference location point to the GPS location points (Frair et al. 2010). I calculated the average fix rate, HDOP, time to fix (TTF) and fix measurement error overall and also for each habitat type. I used one-way ANOVAs and Tukey’s multiple comparison post hoc tests to assess HDOP values, time to fix and fix measurement error as a function of habitat type. The effect of HDOP value and TTF on fix measurement error was assessed using general linear regression.

Precision of fixes was categorized in three levels based on fix type and HDOP values. “Low precision” fixes were any fixes with a HDOP value greater than five.

“Medium precision” fixes were 2D fixes with a HDOP value less than or equal to five.

“High precision” fixes were 3D fixes with a HDOP value less than or equal to five.

These categories were based on similar standards used in previous research testing GPS technology (Frair et al. 2010, Mattisson et al. 2010). The average fix measurement error was calculated within each precision category by habitat type. Also, for each habitat type, the proportion of fixes in each precision category was calculated.

Collar Programming and Deployment

Programming for deployment was chosen as a compromise between amount of data collected and battery life. Due to the GPS collar weight requirements of 65g, battery life was limited. I programmed collars to a fix interval of seven hours, which results in 3-4 fixes per day and a fix attempt for every hour of the 24-hour cycle within seven days. For TTF, 75% were set at 90 seconds and 25% were set at 60 seconds to test fix acquisition rates for both settings without potentially sacrificing fix rate. The additional fix time feature was set to 45 seconds for all fix attempts to give a maximum fix acquisition time of 135 seconds. If fixes were consistently achieved in less time, battery life would be slightly extended. These settings gave an expected GPS battery life of approximately 30 weeks and a maximum of 670 fixes per collar. Once collars were programmed, the data port needed to be sealed at the time of deployment. This was done with a small rubber plug and latex sealant provided by the manufacturer.

The VHF frequency drift and signal strength were assessed during pre-deployment testing; battery life and overall functioning were assessed during deployment. The frequency range was 166-168.999 MHz with a pulse rate of 55ppm.

The VHF battery is separate from the GPS battery and had an expected battery life of 28 weeks. More emphasis was placed on assessment of GPS technology as VHF is not a new technology and has long been used on foxes and other small animals.

Fieldwork was conducted from July through December in both 2009 and 2010 during annual trapping. NPS staff conducted annual trapping for population monitoring. We deployed 14 GPS collars (Quantum 4000E Mini Collars, Telemetry Solutions Concord, CA), eight store-on-board and six remote download models, on male island foxes caught on trapping grids and line transects. Four collars were deployed on the ladder grids and the remaining ten on the line transects (Fig. A.1.3). Ladder trapping grids consisted of 12 box traps (23x23x66cm, Tomahawk Live Trap Co., Tomahawk, WI) in two parallel lines (2x6); a design from Ruben et al. (United States 2007a). Traps were spaced every 200m, baited with dry kibble and loganberry lure. Traps were checked every 24 hours and were open for six consecutive nights during the first portion of the trapping season (July-September). During the second phase of trapping (October-December), line transects were used along roadways. Traps were spaced 200m apart, numbers ranged from 10-40 traps, and traps were run for 3-5 nights (Fig. A.1.2).

Collars were deployed on a random sample of male foxes caught on the east side of the island during annual trapping to facilitate monitoring, recapture efforts and carcass recovery if necessary. Due to the small sample size, the focus was put on males to minimize variation among individuals and to assess home range overlap among neighboring individuals (Chap. 3). Also, in order to meet the limit of 4% or less of body mass required for collaring island foxes, collars were only deployed on male foxes

greater than 1 year of age that weighed 1.65 kg or more. Weights of collared foxes ranged from 1.75-2.6 kg resulting in unit/fox mass ratios of 2.5-3.7%.

Remote Download Data Collection

Remote download capability was assessed during pre-deployment testing and also during deployment. Testing was done with three types of antennas: a small whip antenna that was provided with the remote download base station, a fixed six element 10.2 dB yagi antenna purchased from Telemetry Solutions, and a gold-plated fixed three element 7.1dB yagi antenna (Laird Technologies-Chesterfield, MO). Downloads were attempted from the ground using a laptop computer attached to the base station and each of the three types of antennas. Downloads were also attempted from a small fixed-wing aircraft (Parte Nova Observer) with the fixed three element yagi antenna mounted to the aircraft. Programming and battery life could be checked and updated while connected to the collar.

Data Retrieval and Collar Performance Assessment

Extensive attempts were made to recover the 14 deployed collars from July 2010 until January 2011 using grid, line transect and target trapping methods. Remote downloads were also performed prior to the trapping season to obtain partial data sets before collar batteries expired. Recapture efforts were based on deployment data due to premature failure of the VHF transmitters, which is addressed in the results section.

Upon recapture of GPS collared foxes, health assessments were performed with attention to any potential injuries caused by collars. In addition, fox weights were

collected to compare to weights at the time of deployment. Overall collar condition was also assessed to determine durability of collars.

Data were downloaded from collars and filtered to remove a small number of duplicate fixes and obvious GPS errors such as five fixes in the ocean. Battery life of the GPS component was determined. Data were separated into all fix attempts and successful fixes only and an average with standard error was calculated per collar. The average fix rate, HDOP and TTF were also calculated. The average number of 2D and 3D fixes was determined. The same precision categories used for habitat testing were also used to assess deployed collar data. The percentage of fixes in each precision category were also calculated. I used linear regression analyses to assess individual collar fix rates by hour of the day to determine if there was any relationship between decreased fix rates at certain times of day. The same was done with HDOP values by hour of the day. If decreased fix rates or high HDOP values at certain times of the day were consistent across all collars, this could be attributed to temporal variation in satellite position and availability (Cain et al. 2005). If results were inconsistent across individuals, this could be attributed to behavioral differences in habitat use or activity patterns could affect fix rate and HDOP values (Mattisson et al. 2010). Results are reported using a significance level of $\alpha = 0.05$ and all data are given as mean $\pm$ standard error.

RESULTS

Stationary Pre-Deployment Collar and Software Testing

The collar software and user's manual were fairly user friendly, although multiple updates were made to the manual and software during the period of our project. One

main problem was vague directions about deactivating the GPS units, which resulted in unnecessary battery usage.

Pre-deployment test results were moderately successful. All collars followed programming except one collar had inconsistent time intervals during testing. This collar also had a very rapid pulse rate for the VHF unit. Overall fix rate and time to fix were highly successful; only three tests had a single missed fix and time to fix ranged from 62-109 seconds.

A data download issue encountered was an unknown error message (“error 76”) that prevented data downloads and caused the software program to shut down. This occurred with seven collars and required the collars to be returned to the manufacturer. These issues were all repaired, except one collar was returned without a functioning battery and had to be returned to the manufacturer a second time.

Results across all 16 habitat tests showed a high fix rate of 99.4%, average HDOP of 2.4, average time to fix of 27 seconds, and average fix measurement error of 8.2 meters. Scrub had the highest average ($\pm$ SE) HDOP of 2.8 ± 0.2 and ANOVA results were significantly different ($P < 0.01$) from grassland at 2.1 ± 0.2 , and woodland at 1.7 ± 0.1 (Table 2.1). Woodland habitat time to fix (35.9 ± 1.3 seconds) was significantly higher ($P < 0.01$) than grassland (21.8 ± 1.3 seconds) and scrub habitat (25.4 ± 0.7 seconds). One-way ANOVA showed a significant difference ($P = 0.01$) in fix measurement error between grassland (3.5 ± 0.3 meters) and woodland (11.7 ± 2.9 meters) habitats (Fig. 2.2). There was a significant linear association ($P < 0.01$) between HDOP values and GPS fix measurement error (Fig. 2.3). There was no linear association ($P = 0.40$) between the time to fix (TTF) and fix measurement error.

All grassland fixes were high precision ($3D, HDOP \leq 5$) with an average ($\pm SE$) fix measurement error of $3.5 \pm 0.3m$ (Table 2.2). Scrub habitat had just under 10% of fixes in each of the low and medium precision categories (Fig. 2.4). The average fix measurement error for low and medium precision categories was $24.5 \pm 11.1m$ and $6.5 \pm 0.9m$ respectively for scrub habitat. Approximately 80% of the scrub fixes were in the high precision category with an average fix measurement error of $7.2 \pm 0.7m$. Woodland had approximately 96% of fixes in the high precision category with an average fix measurement error of $11.6 \pm 3.0m$. There was only one medium precision fix with a measurement error of 17m. There were no low precision fixes in woodland habitat and the only missed fix attempt was in woodland habitat.

Collar Programming and Deployment

Programming of deployed collars was mostly successful though some issues were encountered. One collar did not have any fix attempts programmed for 3 different hours of the 24 hour period. Also, there were four collars with one daily template duplicated. This resulted in a higher number of fix attempts at certain hours of the 24 hour cycle. For example, one daily template had fixes programmed at 7:00am, 2:00pm and 9:00pm. These times would have more fix attempts than other hours. It is unclear if this was a program malfunction or user error. Overall, the collars followed programming schedules accurately.

The design of the units was rather bulky with protrusions from the top of the collar and the bottom of the housing unit. Collar deployment was fairly easy although the

hardware to attach collars was larger than necessary, which added weight. Sealing the data port was a messy and slow process that was inconvenient to perform in the field.

Remote Download Data Collection

Only one remote download performed with the small whip antenna was successful out of ten attempts and required less than a 10m range for a successful download. Two tests were done with the six element yagi; one failed and the other was successful. The main issue was the cumbersome size (~5 feet long, non-folding) that was impractical for field use. The three element yagi was the most successful and was used both on the ground and aerially. Remote download was possible within 300m of the collared fox using the base station connected to a laptop computer. Once a data connection to the collar was obtained, the data downloaded within 30 seconds. Programming and battery life could be checked and updated while connected to the collar. Five successful remote data downloads were performed. For three foxes, remote downloads provided the only data set for collars due to the inability to recapture the animal during the 2010 trapping season.

Data Retrieval and Collar Performance Assessment

A total of 11 data sets were collected from the 14 collars deployed. This included eight collars collected during annual trapping efforts in 2010 and one collar from a mortality, which was not included in analyses due to the small data set (~3 weeks). An additional three partial data sets were acquired through remote downloads for animals that were not recaptured. No data were recovered from two animals that had store-on-

board collars that were not recaptured during annual trapping efforts. Total trap night effort for retrieving collars was 1,274 trap nights from July 2010 to January 2011.

The VHF transmitters had a 100% failure rate with an average ($\pm$ SE) operation length of 28.8 ± 10.0 days, ranging from 1 to 92 days. Expected VHF operation time was 28 weeks, which was not met by any of the collars. Average observed successful operation time was $13.8 \pm 4.1\%$.

Due to the VHF failure, the mortality sensor was not thoroughly tested. Three collars had a false mortality signal within days of deployment, which was confirmed by live trapping or observation of the animal. The one mortality that was recovered was not transmitting any VHF signal. During the short time that the VHF components were working, the signal strength was very weak, with an approximate range of 100m, often less than line of sight (i.e. unobstructed path between sending and receiving antennas). There was only slight frequency drift noted in collars, about 3 Hz, which is typical of VHF frequencies.

Of the eight foxes recaptured, four had gained weight (0.05-0.40 kg), three had minimal weight loss (0.05-0.30 kg), and one had remained the same weight, resulting in an average weight change of -0.03 kg. The one mortality that was recovered was determined to be of an unknown cause. According to veterinarian necropsy results, there was no evidence that the mortality was related to the GPS collar. No injuries, neck abrasions or accumulation of ticks under the collar were documented among recaptured foxes.

The durability of the collars was moderate compared to other VHF collar designs. Most antennas from recovered collars had some fraying and bending of the wire. One

antenna broke off at the collar attachment site. Another issue was the epoxy eroding away near the transmitter housing edges resulting in exposed wires. One collar had the bottom portion of the transmitter housing break off completely, which may have been the cause of the collar malfunctioning (Fig. 2.5). Another potential issue was the plugs for the data ports. The sealant was not very durable and as a result, four of the nine collars did not have a data port plug upon collar retrieval, which may have affected performance due to water corrosion or dirt accumulation.

The average ($\pm$ SE) operation time of the GPS component of collars was 16.5 ± 1.7 weeks ($59.1 \pm 6.0\%$), with an expected operation time of 28 weeks. Only one collar met full operation time expectations (Table 2.3, Fig. 2.6). During the successful GPS operation time, the collars followed programming accurately.

Across all collars, a total of 4,879 fix attempts were recorded. Total successful fixes were 4,009 with an average ($\pm$ SE) of 347 ± 33 fixes collected per collar. The average fix rate was $82.3 \pm 2.1\%$, average HDOP value was 2.1 ± 0.2 and average TTF was 80.9 ± 2.8 seconds (Table 2.4). An average of 327 ± 31 (89.8%) 3D fixes and 37 ± 16 (10.2%) 2D fixes were collected. Precision categories consisted of just under 5% of low precision fixes, 7% medium precision fixes and 88% were high precision fixes. There was no linear association ($P=0.67$) between the variation of HDOP values and the hour of day (Fig. 2.7). Similarly, fix rate did not vary by hour of day ($P=0.40$) (Fig. 2.8).

DISCUSSION

Our review of miniaturized GPS collar technology showed moderately successful functionality but there were also components that failed or minimally met expectations of

performance. The problems were collar durability issues, reduced GPS battery life, and failure of the VHF component. Successful results included remote download, which allowed for data recovery from animals that were not recaptured. Pre-deployment habitat tests showed minimal fix measurement error in all habitat types, which provides support for the habitat analysis results. Also, large data sets were obtained with a high fix rate and an even distribution of fixes throughout all times of the day.

The design and durability of the units could still be improved upon to create a more streamline unit that may also result in less external damage during deployment upon animals. The excessive size of the collar hardware seems ironic as decreasing collar weight was a main goal and this is a simple aspect to change. Most recovered units had antenna fraying or bending and some had antennas missing. These antenna problems could likely be linked to the VHF transmitter problems that were encountered. One collar had the bottom portion of the housing unit break off, which likely caused the unit to malfunction. This also could have potentially caused injury to the animal.

For animals that collars were deployed on, there were no obvious signs of injuries (abrasion, hair loss, excessive weight loss) upon recapture and removal of the collars. One mortality occurred during the study but there was no indication that the GPS collar contributed to the cause of death. Overall, our results showed the collars were of a safe weight and design to be deployed on island foxes and could potentially be used on other smaller study organisms. It is understandable that with the miniaturization of the units, design and appearance may be compromised. However, durability should still be a priority to ensure proper functioning.

The actual battery life of GPS collars fell short of expected battery life and units functioned for just under 60% of expected life. It is unclear whether this was due to issues with the software and determining accurate expected battery life or actual GPS battery malfunctions. This supports the idea that battery life is still the main limitation in miniaturization of GPS technology. Further improvements should be made to meet expected battery life as this may provide many problems for data analysis if a key period of data is not obtained due to premature battery failure. This was not ideal performance but GPS collars still provided a greater data set than could have been obtained via traditional VHF telemetry locations. Overall, the programming was very convenient with multiple options to address study objectives while also maximizing battery life, as long as the battery life is achieved.

The VHF component of the collars had essentially a 100% failure rate, which is unacceptable considering this is not a new technology. The explained cause for this was a bad batch of batteries for operating the VHF units, although similar failures also occurred on a kit fox (*Vulpes macrotis*) project in Arizona using the same units (State of California 2011b). Telemetry Solutions has since discontinued purchasing materials from this supplier but it does not resolve the issues involved with our study. This may be more an issue of a poor quality product or possibly just problems with the miniaturized GPS collar model. Without a functioning VHF component, there was no way to track animals or determine if a mortality had occurred. Despite these issues, we were able to recapture eight foxes, recover one mortality and obtain partial data sets via remote downloads for an additional three foxes. This is a reasonable recapture rate without having the advantage of VHF transmitters for tracking. Recapture rates likely vary

among study organisms and should be considered when planning a GPS study and data retrieval methods.

The remote download feature was a good investment to increase the potential for retrieving data, even if only a partial data set. There were some problems with efficiency of antennas for downloads, but once the proper antenna was acquired, remote downloads were highly successful both from the ground and aurally. This also allowed for checking on programming and battery life while the collar was deployed and programming could be altered if desired. Even with the failure of the VHF component, remote downloads were still possible aurally by scanning for all animals in the area where first captured.

Our pre-deployment test results were useful in assessing the level of fix measurement error, fix rate and precision within different habitat types that could be expected from the deployed collar data. Overall fix rate for habitat pretesting was very high at 99.4%. Pretest results showed a significantly higher fix measurement error (11.7m) in woodland compared to grassland (3.5m) and also significantly higher HDOP values (2.8) in scrub. The higher location error in woodland versus grassland was expected based on canopy cover interference, which reduced fix rates by 1-25% and location precision by 12-17m in other studies with canopy closure of 0-70% (Frair et al. 2010). The results of this study are still much lower than the reported fix measurement error (200-600m) with traditional VHF triangulation locations (Zimmerman and Powell 1995). The high fix rate results in pre-deployment testing are likely attributed to the short interval between programmed fixes. This is due to GPS collars maintaining contact with satellites, which allows for a higher fix rate (Moen et al. 1996). The higher HDOP values in scrub habitats could be attributed to the density of the vegetation and the

topography of canyon bottoms, which is where scrub habitat dominates on the island.

Other GPS studies reported 52-71% of location error based on rugged terrain and canopy closure (Lewis et al. 2007).

By using a combination of data parameters, precision of fixes can be better quantified to assess the quality of data collected. Previous studies suggested HDOP and fix type were good indicators of fix precision (Moen et al. 1996, D'Eon et al. 2002). Our results showed a positive correlation between higher HDOP values and GPS fix measurement error, as reported in other studies. Grassland fixes were all categorized as high precision, scrub had 80% high precision fixes and woodland had 96% high precision fixes. The percentage of high precision fixes within scrub habitat can likely be attributed to the fact that most scrub habitat on the island is found in canyon ravines. The canopy cover in combination with topography can have a negative effect on fix precision. Due to the continually improving quality of GPS technology and also satellite availability, future studies may use different precision categories. Using only 3D fixes and a lower HDOP cutoff may result in more precise data but could also potentially eliminate rare, hard to acquire locations.

Retrieved GPS collar data showed overall high performance in main assessment categories of fix rate and precision, with moderate performance in operation time. For retrieved collar data, 88% of fixes were categorized as high precision (3D, HDOP<5) with an average HDOP of 2.1. The average fix rate of 82% was comparable to the 80% fix rate results from a study done on Eurasian lynx (Mattisson et al. 2010).

The closest related study for comparison was done using Televilt GPS collars on foxes at Santa Catalina island looking at habitat use following a recent fire (J. King-

Catalina Island Conservancy, pers. comm.). Fix rate (average 36%, range 20-56%, n = 17) was much lower for that study. Also, the Televilt collars collected an average of 96 GPS locations over three months compared to an average of 365 GPS locations over four months for the Santa Rosa study, using similar time intervals (8 and 7 hours respectively). This could be attributed to the differences in habitat and topography between the islands or potentially the different GPS collar company used.

From the high quality pretest results, it was assumed a similar level of precision and functionality was achieved with deployed collars. Assessment of the retrieved collar data also supported this. For these reasons, the data was deemed sufficiently spatially accurate to use to examine habitat and landscape use of foxes, especially when using Euclidean distance analysis methods, which incorporates a low level of assumed GPS location error.

Recommendations

Based on the results from this study, I recommend performing pre-deployment tests to assess study area precision level and also overall functionality. This will allow for better interpretation of habitat selection results inferred from GPS data. Investment in the remote download feature greatly improves the odds of acquiring at least a portion of the data set. I also recommend purchasing a three element yagi, which works for remote downloads from the ground and aerially. A last recommendation for managers is to assess their specific objectives to determine if GPS collar technology is the best tool before investing the money. This should not be thought of as a replacement for VHF technology, which is still a very useful tool that can obtain similar data at a reduced cost.

GPS technology still needs to be reviewed and improved to better understand some of the inherent bias, including the short battery life. A recommendation for the manufactures is to improve durability in the antennas and modify the GPS collars to create a more streamlined design to improve safety and minimize intrusion on the animal (i.e. broken pieces causing injury, not getting caught on vegetation).

TABLES

Table 2.1: Habitat test summary of average ($\pm$ SE) HDOP values, time to fix (TTF) in seconds and average distance (meters) from fix location to reference point location for each habitat type.

Habitat	HDOP	TTF	Distance
Grassland	2.05 ± 0.15	21.81 ± 1.33	3.52 ± 0.30
Scrub	2.83 ± 0.18	25.43 ± 0.71	8.75 ± 1.26
Woodland	1.68 ± 0.09	35.86 ± 1.32	11.74 ± 2.92

Table 2.2: Average ($\pm$ SE) fix measurement error in meters, within each precision category by habitat type. Dash indicates no values for that precision category.

Habitat	Low Precision ¹	Medium Precision ²	High Precision ³
Grassland	-	-	3.50 ± 0.30
Scrub	24.50 ± 11.12	6.50 ± 0.89	7.20 ± 0.73
Woodland	-	17.00^4	11.60 ± 2.98

1. Any fix (2D or 3D), HDOP>5

2. 2D fix, HDOP $\leq$ 5

3. 3D fix, HDOP $\leq$ 5

4. Only one measurement, no standard error

Table 2.3: VHF and GPS operation time and percent successful operating time. Asterisks indicate partial data sets for collars not retrieved that had remote download capability.

FoxID	VHF Operating Time (Days)	GPS Operating Time (weeks)	Successful GPS Operating Time %
M15*	1	15	53.6%
M33	33	22	78.6%
M48	32	10	35.7%
M52	87	28	100.0%
M64	9	16	57.1%
M66*	1	14	50.0%
M69	30	19	67.9%
M71	30	22	78.6%
M72	92	11	39.3%
M73	1	12	42.9%
M75*	1	13	46.4%
Avg	28.8	16.5	59.1%
SE	10.0	1.7	6.0%

Table 2.4: Summary of fix type, average fix rate, average HDOP, average TTF and percent of low, medium and high precision fixes for each fox.

FoxID	2D Fixes	3D Fixes	Fix Rate	Avg HDOP	Avg TTF	Low	Fix Precision	
							Medium	High
M15	9	431	89.6%	1.7	80.5	2.0%	1.6%	96.4%
M33	32	418	82.6%	1.9	82.6	4.2%	4.7%	91.1%
M48	19	203	88.4%	2.2	84.8	5.0%	5.9%	89.2%
M52	194	330	72.0%	3.5	53.3	15.8%	26.1%	58.0%
M64	12	290	76.6%	1.8	84.5	3.6%	2.6%	93.7%
M66	25	415	92.8%	1.8	82.3	3.2%	4.3%	92.5%
M69	18	412	87.2%	1.9	80.6	3.3%	3.0%	93.7%
M71	29	452	85.6%	2.0	89.2	3.7%	3.7%	92.5%
M72	15	219	81.3%	1.9	85.4	5.1%	5.1%	90.6%
M73	31	191	72.8%	2.5	83.4	12.2%	12.2%	82.4%
M75	23	241	75.9%	2.1	83.0	7.2%	7.2%	89.0%
Average	37	327	82.3%	2.1	80.9	4.9%	7.0%	88.1%
SE	15.9	30.7	2.1%	0.2	2.8	1.1%	2.1%	3.2%

FIGURES

Figure 2.1: Telemetry Solutions GPS collars (Quantum 4000E Mini Collars).

Figure 2.2: Average GPS fix measurement accuracy by habitat type with error bars representing standard error.

Figure 2.3: Scatterplot of HDOP value by fix measurement error. There was a positive linear association between HDOP value and fix measurement error.

Figure 2.4: Percentage of GPS fixes in low, medium and high precision categories, including percentage of failed fixes for each habitat type from pre-deployment habitat tests.

Figure 2.5: Recovered GPS collars with broken canister, missing antenna and frayed antenna.

Figure 2.6: GPS operating time relative to expected battery life and the average across collars. Asterisks indicate partial data sets for collars not retrieved that had remote download capability.

Figure 2.7: Scatterplot of HDOP value by hour of the day for each fox. Linear regression showed no correlation between HDOP and hour of day.

Figure 2.8: Scatterplot of fix rate by hour of the day for each fox. Linear regression showed no correlation between fix rate and hour of day.

III. Home Range Characteristics and Habitat Selection of Island Foxes (*Urocyon littoralis*)

INTRODUCTION

Determining habitat use of a species is fundamental in developing management strategies, particularly for endangered species that are conservation reliant (Morrison et al. 1998). Species endemic to islands, particularly with small populations, run a much higher risk of extinction than mainland species due to system perturbations (Carlquist 1974), which often come in the form of novel predators or habitat destruction. Studies that incorporate home range size and habitat use data with demography can achieve a better understanding of population dynamics (Powell 2000). Knowing what types of habitat resources are available and used by a species at low density is more informative of habitat quality compared to habitat selection at high densities (Van Horne 1983).

Island foxes (*Urocyon littoralis*) are endemic to six of the eight Channel Islands off the coast of southern California. From 1994 to 1999, the Santa Rosa Island population declined from about 1,500 to 14 with similar declines seen on the other islands (Coonan et al. 2005b, Roemer 1999). The declines seen in the northern islands were primarily due to predation by non-native golden eagles (*Aquila chrysaetos*), which can also be linked to the non-native ungulate prey base on the northern islands (Roemer 1999). The non-native deer (*Odocoileus hemionus*) and elk (*Cervus canadensis*) populations and historical ranching operations on Santa Rosa caused severe habitat degradation. Due to drastic population declines in 2004, the subspecies on four islands were listed as federally endangered (United States 2004).

Prior to decline, island foxes have been described as “generalists” and occupied all habitat types found on the islands including grassland, coastal sage scrub, lupine scrub, chaparral, mixed and riparian woodland and coastal marsh areas with the types of habitats available varying by island (Laughrin 1977, Moore and Collins 1995). Typically, the southern islands have a lower diversity of habitats along with a drier climate. The larger northern islands, specifically Santa Cruz and Santa Rosa, have much more diverse habitats and terrain and receive more annual rainfall.

To date, no research has been published relating to home range and habitat use for island foxes on Santa Rosa. The island fox population declined to near extinction and is now in the beginning phases of recovery. Santa Rosa has had the slowest recovery rate of all the islands (Coonan 2010). Also, due to the recent removal of non-native ungulates, the habitat conditions are changing as restoration efforts are being conducted. The current low fox density provides the opportunity to investigate habitat use and selection in the absence of competition pressure when the most resource abundant habitat types are available.

Our specific objectives were to: 1) determine home range area, overlap and seasonal variations; 2) determine habitat composition of kernel density isopleth home ranges; 3) assess second, third and fourth order selection of habitat and topography; and 4) determine seasonal and time of day patterns in selection of habitat and topography within home ranges.

Due to the current small population size and low densities, I predict that home range sizes will be larger than reported for other islands with higher densities and that home range overlap will be minimal. Due to the small samples sizes for season data and

results from previous studies, I predict no seasonal differences in home range area.

Based on past island research, I predict that foxes will use all habitat types with higher use of scrub habitats, which provides more cover and potential resources.

METHODS

Study Area

Santa Rosa Island (33° 57' N, 120° 05' W) is one of the northern Channel Islands that are part of Channel Islands National Park. It is the second largest (217 km²) of the eight California Channel Islands (Fig. 1.1). It is characterized by a Mediterranean climate with a marine influence. Topography of the island includes a central ridge with multiple canyons radiating out from the center of the island towards the coastline. Maximum elevation is 484 m. Habitat types include coastal grassland, island chaparral, scrub oak woodland, coastal sage scrub, coastal bluff scrub, riparian woodland, Torrey pine forest and bishop pine forest (Schoenherr et al. 1999). The study site encompasses the eastern half of the island.

Fox Trapping and Collar Deployment

Since 1999, the National Park Service has conducted annual trapping of Island Foxes to monitor general health, vaccinate for canine distemper virus and rabies, replace or deploy new VHF radio collars for survival monitoring, identify new young of the year, and estimate density and population size for the island. Data collected for each animal included weight, temperature, health/ injury check and body condition score, teeth wear age, vaccinations and parasite load. New individuals were tagged with passive integrated

transponder (PIT) tags (Biomark, Boise, ID) and 5-10mL of blood was drawn for sample archiving or health assessment if necessary.

Project fieldwork was conducted from July through December in both 2009 and 2010. Ladder grids consisted of 12 box traps (23x23x66cm, Tomahawk Live Trap Co., Tomahawk, WI) in two parallel lines (2x6), a design by Ruben et al. (United States 2007a). Traps were spaced every 200m, baited with dry kibble and loganberry lure. Traps were checked every 24 hours and were open for six consecutive nights during the first portion of the trapping season (July-September). During the second phase of trapping (October-December), line transects were used along roadways. Traps were spaced 200m apart, numbers ranged from 10-40 traps, and traps were run for 3-5 nights (Fig. A.1.2). We deployed 14 GPS collars (Quantum 4000E Mini Collars, Telemetry Solutions Concord, CA), eight store-on-board and six remote download models, on male island foxes caught on trapping grids and line transects. Four collars were deployed on the ladder grids and the remaining ten on the line transects (Fig. A.1.3).

Collars were deployed on a random sample of male foxes caught on the east side of the island during annual trapping to facilitate monitoring, recapture efforts, carcass recovery if necessary and to assess home range overlap. We deployed all of our collars on males to eliminate possible variation due to sex and overlap of data for mated pairs. Also, in order to meet the limit of 4 percent or less of body mass required for collaring island foxes, 65g collars were only deployed on male foxes greater than 1 year of age that weighed 1.65 kg or more. Weights of collared foxes ranged from 1.75-2.6 kg resulting in unit/fox mass ratios of 2.5-3.7 percent.

Collar programming was a compromise between amount of data collected and battery life. Due to the GPS collar weight limit of 65g, battery life was limited. I programmed collars to a fix interval of seven hours, resulting in 3-4 fixes per day and a fix attempt for every hour of the 24-hour cycle within seven days. A fix is equal to a location on the animal. For time to fix (TTF), 75% were set at 90 seconds and 25% were set at 60 seconds to test fix acquisition rates for both settings without potentially sacrificing fix rate. The additional fix time feature was set to 45 seconds for all fix attempts to give a maximum fix acquisition time of 135 seconds. If fixes were consistently achieved in less time, battery life would be slightly extended. These settings gave an expected GPS battery life of 28 weeks and a maximum of 670 fixes per collar.

Habitat Classification

At the onset of our study, the most current vegetation data available for Santa Rosa Island was a 1990 map based on aerial photographs from 1988. This contained 20 land cover and vegetation categories that were digitized from hand-attributed USGS 1:24,000 topographic maps. When overlaid on current aerial imagery, it was evident that the data did not accurately represent current vegetation boundaries. A new vegetation shape file for Santa Rosa Island based on 2009 aerial photographs was in development by NPS staff; however, this had not been completed for the entire study area at the time of our project.

To provide a more complete, current and accurate vegetation layer for this study, interactive supervised image classification was conducted using ArcGIS 10 (ArcGIS Desktop 2011) on one meter resolution color infrared aerial imagery (NAIP) from 2009.

We defined six general habitat types: bare ground, chaparral, coastal scrub, grassland, lupine scrub and woodland. Initial classification results were smoothed using the Focal Majority tool with a 5 x 5 m moving window followed by the Boundary Clean tool. Following classification, a 1m resolution LiDAR digital elevation model (DEM) with 15cm vertical accuracy and a digital surface model (DSM) were used to further distinguish vegetation types based on height. Specifically, a vegetation height threshold of 4m was used to separate woodland vegetation from chaparral and other vegetation types. The resulting classification and polygon boundaries were reviewed and manually edited with input from NPS botanist, Dirk Rodriguez, to assess suitability and accuracy (See Appendix 2 – Habitat type mapping on Santa Rosa Island through image classification).

Study Area Delineation

Once the collars and data were retrieved, the study area was delineated using the complete set of fixes (Fig. A.1.4) to create a 100% minimum convex polygon (MCP). This polygon was clipped using an island mask layer to remove any ocean portions. The total area and percent composition of each habitat type were then calculated within the study area.

Home Range Estimation: Minimum Convex Polygon

Individual fox home ranges were delineated using fix data and the Home Range Tools plug-in (Rodgers et al. 2007) for ArcGIS 9. I created 50% and 95% MCPs for each fox using a fixed mean approach, which is comparable to other home range studies

(Harris et al. 1990; White and Garrott 1990). Polygons along the coast were clipped to the island mask layer to exclude ocean areas. ArcGIS was used to calculate the area of each polygon to determine the home range size of individual foxes. I used linear regression analyses to assess the relationship between MCP area and number of fixes, fox weights and proportion of dominant vegetation. Overlap area of 95% MCP polygons between neighboring individuals was calculated using the Intersect tool in ArcGIS, and the proportion of overlap relative to each home range size (HR1 and HR2) was calculated using a mean overlap formula (Minta 1993):

$$\text{Mean Overlap} = \sqrt{\frac{\text{overlap}}{\text{HR1}} \times \frac{\text{overlap}}{\text{HR2}}}$$

Home Range Estimation: Kernel Density Isopleth

Kernel density isopleths (KDI) were created using Geospatial Modeling Environment (GME) software, version 0.5.3 (Spatial Ecology LLC 2011) and ArcGIS 10. The Kernel Density Estimate command was run with a default Gaussian kernel, the bandwidth was set using plugin optimization and the output cell size was 10m. Both 95% and 50% isopleths (percent volume contours) were then constructed using the Isopleth command in GME. Isopleth polygons were clipped to the island mask layer to exclude ocean areas, and the area for each polygon was calculated in ArcGIS. Area overlap of 95% and 50% KDIs was calculated using the same methods as for the MCPs. In addition, 95% KDIs minimum overlap volume proportion was calculated using methods described in Kerston and Marzluff (2009).

To examine seasonal differences in habitat use, seasonal 95% and 50% KDIs were created for each fox. We defined two seasons, Fall (Sept. 15 –Dec. 15) and Winter

(Dec. 16 – Mar. 30), based on weather, phenological changes in vegetation, fox activity patterns and prior studies (Laughrin 1977, Roemer et al. 2001, Crooks and Van Vuren 1996). Most precipitation on the Channel Islands occurs from late December through February and the dry season is May through October. Males typically are more active during the Fall while looking for mates, and are less active during the Winter reproductive season (Laughrin 1980, Roemer et al. 2001). A paired t-test was used to compare seasonal home range size for the eight foxes that had data for both seasons.

To assess habitat use by time of day, each fix was allocated to one of three diel categories based on the recorded GPS fix time. Categories created were day, night and crepuscular. “Crepuscular” consisted of the dawn and dusk periods, which were defined as the two hours before and after sunrise and sunset. Daily sunrise and sunset times for the project period were obtained from the United States Naval Observatory website (http://aa.usno.navy.mil/data/docs/RS_OneYear.php). “Day” and “night” covered the remaining 8 hours after sunrise and 8 hours after sunset respectively. Each fix was categorized as one of the three time of day categories based on the recorded GPS time.

Habitat Selection Using Euclidean Distance Analysis

Euclidean distance-based analysis (EDA) was used to quantify habitat selection based on observed GPS locations compared with random point locations representing expected use. The EDA approach measures the linear (Euclidean) distance from each fox location and random point to the nearest feature of each habitat type. A distance ratio is then created for each habitat type and each fox by dividing the mean of the observed fox location distances by the mean of the random point distances (Conner and Plowman

2001). Distance ratios greater than 1.0 indicate avoidance of habitat and ratios less than 1.0 indicate selection of habitat.

To thoroughly investigate habitat use and selection, habitat analyses were conducted using EDA at three levels of selection: second order selection within the study area, third order selection within the 95% KDI home range and fourth order selection within the 50% KDI core area (Johnson 1980). To assess selection within the study area, the Create Random Points tool in ArcGIS was used to create 10,000 random points within the study area. Random points were then intersected with the 95% KDI isopleths to create random points (~5,000) bound by the isopleths. A raster-based approach was used to measure linear distances from each point to the nearest habitat representative of each type using the Euclidean Distance tool. The Extract Multi Values to Points tool was used to extract distance values for each habitat type for all points. Distances were then averaged for each habitat type.

Second order habitat ratios were created by dividing the average distance to each habitat type from random points within the home range by the average distance to each habitat type from random points within the study area. This gave a total of six habitat ratios, one for each habitat type. Population level averages were calculated by first natural log transforming ratios for individual foxes. All ratios were analyzed in SAS using a general linear model/MANOVA to test whether habitat use differed from random (Conner and Plowman 2001). Ratio averages were exponentiated and reported with standard error.

To assess selection within the 95% KDI home ranges (third order selection), the Create Random Points tool in ArcGIS 10 was used to create 1,000 random points within

each home range. The same techniques as described above were used to calculate average point distances to each habitat type. Third order habitat ratios were created by dividing the average distance to each habitat type from GPS location points within the home range by the average distance to each habitat type from random points within the home range. This gave a total of six habitat ratios that were analyzed using the same methods as described above.

To assess selection within the 50% KDI core areas (fourth order selection), similar techniques were used as with third order selection except GPS location points were bound within the core area. Fourth order habitat ratios were created by dividing the average distance to each habitat type from the GPS location points within the core area by the average distance to each habitat type from random points within the home range. Similar statistical analyses were performed as previously described.

As a follow up, the fixed effects of season (Fall and Winter) and time of day (Crepuscular, Night, Day) were tested for third order habitat selection. Fox ID was included as a random effect to account for individual differences. If the MANOVA fixed effect results were significant, individual habitat type results were examined. An orthogonal contrast statement was used in SAS to compare selection between categories (Fall vs. Winter, day vs. night, crepuscular vs. day and crepuscular vs. night) within habitat types.

Topographic Position Index Analysis

Topographic position index (TPI) analysis (Jenness 2006) was conducted in ArcGIS 10 to investigate topography use and selection. TPI is determined by evaluating

terrain relative to a generalized or smoothed surrounding terrain. Topography is categorized as “ridge” if the area is greater than the generalized surrounding terrain and “valley” if the area is less than the generalized surrounding terrain. A 3m resolution LIDAR DEM was used and mean elevation was determined using a 500m window. Residuals are used to determine deviations from the mean elevation and are categorized into terrain classes in a TPI raster layer. TPI classes were 1 = Valley Bottom, 2 = Low Slope, 3 = Mid Slope, 4 = Upper Slope and 5 = Ridge (Jenness 2006).

EDA was also used to evaluate topographic selection. The same methods were used to determine second order selection within the study area, third order selection within the 95% KDI home range, and fourth order selection within the 50% KDI core area. Also, the topography data were analyzed with a mixed effect model similar to the habitat data. Third order topographic ratios were used to test for selection with season and time of day as main effects and fox ID as a random effect. Follow-up orthogonal contrast statements were used to compare selection between categories if necessary. Results are reported using a significance level of $\alpha = 0.05$ and all data are given as mean $\pm$ standard error.

RESULTS

Study Area Delineation

The study area encompassed 72.7 km² with grassland as the dominant vegetation type, occupying the largest area at 54.7%. The next two most common vegetation types were scrub at 24.1% and chaparral at 8.8% (Table 3.1).

Data Retrieval

Of the 14 collars deployed, we recovered eight during annual trapping efforts in 2010. Three additional partial data sets were acquired through remote downloads for animals that were not recaptured, for a total of 11 data sets. One collar from a fox mortality was not included in analyses due to its small data set (~3 weeks). No data were recovered for two animals that had store on-board collars that were not recaptured during annual trapping efforts. Total effort for retrieving collars was 1,274 trap nights from July 2010 to January 2011.

Total successful fixes were 4,009 out of 4,879 fix attempts, with an average of 347 ± 33 fixes collected per collar. The average operation time of the GPS component of collars was 16.5 ± 1.7 weeks, representing $59.1 \pm 6.0\%$ of the expected operation time of 28 weeks (Table 2.3, Fig. 2.6). The average fix rate was $82.3 \pm 2.1\%$, average HDOP value was 2.1 ± 0.2 and average TTF was 80.9 ± 2.8 seconds (Table 2.4). An average of 327 ± 31 3D fixes and 37 ± 16 2D fixes were collected.

Home Range Estimation: Minimum Convex Polygon

The mean 95% MCP area was $3.39 \pm 0.59 \text{ km}^2$ and mean 50% MCP area was $1.26 \pm 0.23 \text{ km}^2$ (Fig. 3.1). The mean number of fixes for 95% MCPs was 347 ± 33 and 182 ± 17 for 50% MCPs (Table 3.2). There was no linear association between MCP area and number of points used for both 95% and 50% MCPs ($P = 0.32$ and 0.77 respectively). There was also no linear association between MCP area and weight of foxes for both 95% and 50% MCPs ($P = 0.19$ and 0.57 respectively). Lastly, there was no linear

association between MCP area and the proportion of dominant vegetation type within the home range ($P = 0.62$).

Seasonally, the mean 95% MCP home range area was $2.97 \pm 0.42 \text{ km}^2$ in Fall ($n=11$) and $3.36 \pm 0.97 \text{ km}^2$ in Winter ($n=8$) (Table 3.2, Fig. 3.2). The mean Fall 50% MCP area was $1.17 \pm 0.20 \text{ km}^2$ and mean Winter 50% MCP area was $1.28 \pm 0.33 \text{ km}^2$. There was no significant seasonal difference in 95% MCP area ($P = 0.64$).

The overlap between neighboring pairs of foxes' 95% MCP ranged from 0.08-28.27%, with a median overlap of 5.30%. The overlap area ranged from 0.003-0.18 km^2 with a median overlap area of 0.15 km^2 (Table 3.3). There was no overlap among any of the 50% MCPs, both composite and seasonal.

Home Range Estimation: Kernel Density Isopleth

The mean 95% KDI home range area was $3.82 \pm 0.68 \text{ km}^2$ and mean 50% KDI area was $1.06 \pm 0.23 \text{ km}^2$ (Table 3.2, Fig. 3.3). Most KDI home ranges had two to three 50% core areas. On average, grassland covered the largest area (55.2%), followed by scrub (19.7%) and the least common habitat at 1.4% was woodland (Table 3.4; Fig. 3.4, 3.5).

The mean Fall 95% KDI area was $3.93 \pm 0.70 \text{ km}^2$ and mean Winter 95% KDI area was $3.84 \pm 0.94 \text{ km}^2$. Mean Fall 50% KDI area was $1.17 \pm 0.23 \text{ km}^2$ and mean Winter 50% KDI area was $1.06 \pm 0.27 \text{ km}^2$ (Table 3.2). There was no significant seasonal difference in 95% KDI area ($P = 0.85$).

The 95% KDI overlap volume ranged from 2.11-11.21%, with a median overlap of 6.00%. The overlap area ranged from 0.12-0.77 km^2 with a median overlap area of

0.26 km² (Table 3.5). Overlap was minimal for 50% KDIs with only three pairs having overlap area ranging from 0.003-0.10 km² with a median overlap area of 0.02 km².

Habitat Selection Using Euclidean Distance Analysis

At the second order level within the study area, fox locations differed significantly from random locations ($F_{6,5} = 7.84$, $P=0.020$). Foxes were closer to lupine than expected ($t_{10} = -2.49$, $P = 0.032$). There was no significant difference for other habitat types (Table 3.6, Fig. 3.6).

Within 95% KDI home ranges (third order), no significant habitat selection occurred ($F_{6,5} = 3.36$, $P=0.102$), though there was a slight trend for scrub selection (Table 3.7). Habitat use in core areas (fourth order selection) did not differ significantly from random locations ($F_{6,5} = 1.09$, $P=0.472$). Within 95% KDIs, there was no significant seasonal habitat selection (Table 3.8, Fig. 3.7) at the third order level ($F_{6,2} = 5.83$, $P=0.154$). Within 95% KDIs, there was a significant time of day effect on habitat selection (Table 3.9, Fig. 3.8) at the third order level ($F_{18,71} = 2.35$, $P=0.006$). Grass and bare habitat were both significantly selected at night ($F_{1,30} = 15.54$, $P<0.001$). There was no significant crepuscular habitat selection.

Topographic Position Index Analysis

Topographically, the study area composition was primarily mid slope (47.6%) and steep slope (20.1%); the least represented was ridges at 7.4% (Table 3.10). Within 95% KDIs, topographic composition was primarily mid slope (51.2%), followed by steep

slopes (20.2%), and the least common topography, at 6.4%, was ridges (Table 3.11, Fig.3.9, 3.10).

Within the study area (second order), fox locations did not differ significantly from random locations ($F_{6,5} = 0.33$, $P=0.880$). Within 95% KDI home ranges (third order), significant topographic selection occurred ($F_{6,5} = 4.72$, $P=0.043$, Table 3.12). Foxes were closer to valleys than expected ($t_{10} = -2.96$, $P = 0.014$), and farther than expected from steep slopes ($t_{10} = 2.78$, $P = 0.019$). Within 95% KDIs, there was no significant time of day ($F_{15,72} = 0.68$, $P=0.791$) or season effect ($F_{5,3} = 3.01$, $P=0.196$) on topography selection at the third order level. Within core areas (fourth order), no significant topographic selection occurred ($F_{6,5} = 1.22$, $P=0.401$).

DISCUSSION

This study represents the first detailed analysis of home range and habitat use for Santa Rosa Island foxes and the second use of GPS collars on Channel Island foxes. Though it is a small sample size, it is the most intensive data set ever collected for island fox habitat use. Moreover, Santa Rosa Island's current recovering island fox population has provided an excellent opportunity to examine many aspects of spatial ecology and density dependence. With the lowest density of any of the island fox populations on the Channel Islands (Coonan 2010), it was an ideal time to look at home range size and overlap, and also habitat use and selection within home ranges. Recovery efforts have been successful and populations are increasing with high reproduction and survival rates (Coonan et al. 2010), which allows for incorporating research-based data collection into on-going monitoring and management practices. The island is also undergoing many

ecological changes due to the recent removal of multiple non-native species that have had direct impacts on native island fox populations and their habitat. This study provides essential baseline data to examine density dependent effects as the fox population recovers and increases in density.

Our main findings pertaining to home range and habitat selection included Santa Rosa currently having the largest home range size reported for any island fox population before declines and currently among recovering populations. In addition, there was low overlap of home ranges, which can likely be explained by current low densities. Habitat analysis results showed selection for lupine habitat within the study area. This may be an artifact of the data set but it is worth investigating further to determine if there is any biological significance. The findings for selection of bare and grassland habitat at night could be extended with a study that looks more at activity patterns within different habitats by time of day. This may also give further support to the idea of a rapid behavioral adaptation to the novel predation events of non-native golden eagles (Swarts et al. 2009). Selection for valleys and avoidance of ridges can also further support this idea of predation avoidance behavior. Understanding these population dynamics and ecology will provide necessary insight into developing management and conservation plans.

Home Range Size, Overlap and Density

Island fox populations on Santa Rosa do not match the predicted small home range size and high overlap typical of high density insular vertebrates compared to mainland populations (Stamps and Buechner 1985). Also, when compared to other island

fox populations, this trend is very evident. Our results showed the largest home range size ($3.39 \pm 0.59 \text{ km}^2$ for 95% MCP, $3.82 \pm 0.68 \text{ km}^2$ for 95% KDI) reported for any of the island fox populations (Coonan et al. 2010). In addition to large home range sizes, there was also low overlap of home ranges. The average 95% MCP overlap was 7.2% with no overlap of core areas. The average 95% KDI overlap was 10.4% with 2.8% overlap of core areas. It is assumed that on Santa Rosa, the main factor in these large home range sizes and low overlap was the low density of 0.86 foxes/km^2 (Coonan 2010) at the time of the study.

It is important to keep in mind the ecological differences between the islands when comparing among island fox populations. The southern islands have moderate topography and a drier climate, and as a result, more cactus and desert scrub vegetation. In comparison, the northern islands have more rugged topography and receive higher precipitation amounts. This allows for perennial streams that support riparian and woodland habitats not found on the southern islands. Also, the southern island fox populations did not go through the drastic declines driven by golden eagle predation. In addition to the ecological differences, each of the islands has a different history in terms of human occupation and disturbance. But when the island fox populations are compared to mainland populations of canids, the differences among islands becomes negligible.

Studies on Santa Cruz examining male-male overlap using 95% kernel density isopleth home ranges averaged $0.34 \pm 0.10 \text{ km}^2$ with approximately 30% overlap and 5% overlap of 50% KDIs at densities of $7.0\text{-}7.3 \text{ foxes/km}^2$ (Roemer et al. 1994, Crooks and Van Vuren 1996). Another study on Santa Cruz using 95% MCP home ranges found an average overlap of 11% for non-mated individuals (Roemer et al. 2001).

Support for a negative relationship between home range size and density was recently reported for one of the southern Channel Islands. Home range sizes on San Clemente ranged from 0.21-1.39 km², with the smaller home ranges documented in high density (42.6 foxes/km²) sand dune habitat and larger home ranges in low density (2.9 foxes/km²) grassland habitat (Sanchez 2012). This same density dependent pattern has also been demonstrated for Santa Rosa but with large home range sizes at low density (Fig. 3.12, Table 3.13). Multiple other species also demonstrate similar density dependent relationships with home range size (Trehella et al. 1988, Kjellander et al. 2004, Erlinge et al. 1990). It is still unclear whether habitat type plays a part (Gregory et al. 2012) and further studies need to be conducted.

Other factors shown to have a relationship with home range size are resource availability and metabolic needs (Harestad and Bunnell 1979, Hixon 1980). Island systems typically have high resource availability, which allows for metabolic needs to be met within smaller home ranges, even at high densities (MacDonald 1983, Stamps and Buechner 1985, MacArthur et al. 1972). Insectivorous versus carnivorous diets also result in a smaller area needed for obtaining resources (Gittleman and Harvey 1982). In a dietary analysis of all the islands, Santa Rosa foxes had the highest use of deer mice (*Peromyscus maniculatus*) of all the islands (State of California 2011a), which suggests high resource availability and further supports low density driving the current large home range size. Other studies have documented home range expansion due to predation events or disease related die-off even when resources are abundant (Roemer 1999, Roemer et al. 2001b, Baker et al. 2000). These results support the idea that home range

size may be largely affected by population density and spatial distribution of animals (MacDonald 1983).

Topographic Selection

Our results showed significant selection for valleys and avoidance of upper slopes within the home range (third order). Selection for valleys is biologically relevant given the variety of resources found there. Topography is often correlated with vegetation patterns and can be a good predictor of species distribution (Dickson et al. 2005). A few of the canyons and valleys on Santa Rosa have perennial streams and small pools in the valley bottoms, which would likely be areas highly selected for due to vegetation cover and water sources. Along with water comes an increased diversity and abundance of potential prey items and vegetation that provides cover and protection, as shown by previous carnivore studies (Szor et al. 2008, Donavan et al. 2011). Yet it is unclear if this selection for valleys is a result of the water, the vegetative structure associated with the water or the prey diversity associated with both or simply the cover provided. Anecdotal observations include foxes resting under scrub cover in canyons and dens have also been located in sheltered valley bottoms near water sources. Valley bottoms can also provide shelter from high winds, which is common on the outer Channel Islands. Beyond protection from inclement weather, valley bottoms can also provide cover and protection from golden eagle predation. This may also indicate avoidance of steep slopes, which may be a more vulnerable position for aerial predation. Additional studies that incorporate den location and rest site data may provide further insight.

Habitat Selection by Time of Day

Results showed significant selection for bare and grassland habitats at night. Previous studies have characterized fox activity as partially diurnal with higher activity levels at night (Crooks 1994, Roemer et al. 2001), which supports the importance of collecting night data. One of the main benefits of GPS technology is that it can collect data evenly across the 24 hour day (Dickson et al. 2005) compared to traditional VHF technology methods, which have safety and other logistic issues associated with collecting night data. Higher activity levels at night may be due to foraging for nocturnal prey such as mice and some species of insects. If nocturnal prey activity is occurring in open and exposed areas, such as bare and grassland habitat, which facilitate ease of movement, this would support fox selection for these habitats at night. NPS field staff have reported observations of foxes traveling along dirt roads at night, which are categorized as bare habitat. Use of dirt roads at night by foraging animals has been documented in other studies, although mainly by nocturnal species (Beier 1995, Dickson et al. 2005).

Another potential explanation related to behavioral adaptations, which have recently been examined on Santa Cruz, suggest that using these open and exposed habitat types at night may reduce predation risks. Island foxes likely have evolved with minimal predation risks until the recent influx of non-native golden eagles. Research on Santa Cruz Island, where golden eagle predation also played a major role in island fox population declines, suggested rapid behavioral adaptation to a novel predator (Swarts et al. 2009, Hudgens and Garcelon 2011). Prior to golden eagle predation, foxes exhibited diurnal activity. Research done from 2003-2007, following extensive population declines

due to golden eagle predation, showed a decrease in diurnal fox activity and an increase in nocturnal activity. There is more evidence that this is a heritable behavioral response rather than a learned response due to the low chance of a fox surviving an attack by golden eagle. Island foxes are typically not a social species, mainly only seen in pairs during the breeding season, so that decreases the chances of witnessing a golden eagle attack on another individual. Our findings of selection at night for bare and grassland habitats may give more support to this behavioral adaptation, which could have occurred on Santa Rosa also due to the same golden eagle predation pressure as seen on Santa Cruz. However, there was no significant avoidance of these habitat types during the day, although a trend for avoidance of grassland during the day was detected. Further work would need to be done to verify this, looking more specifically at activity patterns and topography use by time of day of wild born versus captive bred foxes.

Habitat Selection within Study Area, Home Range and Core Area

Determining selection of a species is fundamental to better understanding its resource needs, but use can vary seasonally and at different spatial scales. Discerning preferences and selection from observation of use can be very complicated. Garshelis (2000) examined multiple habitat analysis methods and literature and concisely described the differences in habitat terminology as “use results from selection, selection results from preferences, and preference presumably results from resource-specific differential fitness.” By determining fitness, habitat quality can be assessed and, in theory, lead to a better understanding of selection and preference. The most basic way to assess selection is to compare use to availability and determine if there is disproportionate use. This is

where the methodology and interpretation can become complicated (Neu et al. 1974, Johnson 1980, Aebischer et al. 1993, Conner et al. 2003, Dussault et al. 2005).

Our results showed significant selection for lupine habitat within the study area (second order selection). This result was not expected due to the limited distribution of lupine only in the northeast area of the island. Also, density results from annual grid trapping (Coonan 2009) in this area were low (0.59 ± 0.52 foxes/km² in 2009) compared to average island-wide density (0.86 ± 0.17 in 2009). Also, no previous island fox studies have shown lupine as an important habitat resource. Previous studies have found island foxes to be generalists that inhabit all available habitat types (Laughrin 1977, Moore and Collins 1995), with higher densities in scrub and woodland habitats (Roemer 1999). A more recent study on San Clemente found that habitat was not a significant predictor of density (Gregory et al. 2012).

One potential biological explanation for this is that native lupine scrub habitat is typically found in dune areas of the island and harbors potentially high resource diversity in the form of multiple insect species found in sandy soils. Deer mice (*Peromyscus maniculatus*) and Jerusalem crickets (*Stenopelmatus sp.*) are two of the main components of Santa Rosa island fox diet (State of California 2011a, Moore and Collins 1995) and are found in lupine scrub habitat.

A point to be aware of when using EDA is that selection for a habitat is based on proximity of points to a habitat type relative to proximity of random points to a habitat type. This can result in selection for a habitat that is not used simply due to proximity. The significant selection for lupine habitat within the study area may be a product of this, especially considering that there was no significant selection for lupine at the third order

level within home ranges. The fact that all the recovered data sets for this study were concentrated in the north part of the island near the only patch of lupine habitat may also explain these results.

Third and fourth order selection results were not significant for any habitat types, though there was a trend for scrub habitat selection within home ranges. Larger sample sizes may have given more support to this trend. These results may also simply be credited to a generalist approach of island foxes in terms of habitat and resource use (Laughrin 1977, Moore and Collins 1995). Studies on Santa Cruz showed a preference for fennel-grasslands, which had the highest availability, and lower than expected use of scrub oak and ravine habitats (Crooks and Van Vuren 1996). These data were collected at high fox density levels prior to population declines, which may not be indicative of the most productive habitat, but simply available habitat (e.g., at high densities, some foxes may be forced into marginal habitat).

Recommendations

Based on the results from this study, I recommend assessment of home range size and overlap when population density on Santa Rosa reaches historic levels of four foxes/km². A relevant follow up study could examine home range size and overlap differences of females across multiple seasons to compare with the male data collected in this study. Also, due to the short data collection window of this study, it would be beneficial to collect data for the denning and pupping season. This could also provide a measure of fitness through reproductive success and be linked to habitat data to determine quality of habitat. It is also been previously recommended that population

estimates could be improved by assessing habitat-specific densities (Roemer et al. 1994). Now that most islands are using grid trapping methods, grid specific density and habitat data could be collected. This can provide a more complete picture on the relationship between density dependence on home range size by incorporating density specific habitat data. Further investigation of the potential resources (i.e.-prey inventory study) within lupine habitat could provide more insight into the lupine habitat selection results and potentially determine the habitat quality. Also, continued habitat restoration efforts on this native habitat found in low abundance on the island would contribute to overall island recovery.

TABLES

Table 3.1: Habitat composition of study area (eastern half of Santa Rosa Island).

Habitat Type	Area (km²)	Percent
Grassland	39.7	54.7%
Scrub	17.5	24.1%
Chaparral	6.4	8.8%
Lupine	3.8	5.3%
Bare	3.8	5.2%
Woodland	1.4	1.9%
Total	72.7	100%

Table 3.2: Overall and seasonal home range area for 95% and 50% minimum convex polygons (MCP) and kernel density isopleth (KDI).

	FoxID	95% MCP (km ²)	95% KDI (km ²)	Points Used	50% MCP (km ²)	50% KDI (km ²)	Points Used
Overall	M15	3.26	3.54	420	1.54	1.06	219
	M33	2.61	2.63	428	0.72	0.51	225
	M48	3.02	3.85	211	1.03	1.01	110
	M52	7.31	5.65	498	1.32	0.97	262
	M64	0.77	0.79	287	0.3	0.19	151
	M66	1.31	1.51	419	0.59	0.31	220
	M69	4.53	4.53	409	1.58	1.39	215
	M71	3.94	4.43	457	1.45	1.17	241
	M72	1.27	1.57	223	0.57	0.49	117
	M73	3.56	4.78	211	1.79	1.62	111
	M75	5.73	8.71	251	2.98	2.9	132
	Average	3.39	3.82	346.73	1.26	1.06	182.09
	SE	0.59	0.68	33.17	0.23	0.23	17.46
Fall	M15	3.09	3.32	247	1.29	0.94	130
	M33	2.93	2.88	226	1.05	0.78	119
	M48	3.07	3.85	209	1.03	1.01	110
	M52	4.35	7.81	38	0.77	1.85	20
	M64	0.73	0.79	209	0.28	0.22	110
	M66	1.21	1.43	243	0.52	0.33	128
	M69	4.34	4.9	236	1.74	1.72	124
	M71	3.13	4.22	242	1.35	1.21	127
	M72	1.27	1.59	223	0.57	0.5	117
	M73	3.59	4.74	207	1.81	1.63	109
	M75	4.99	7.7	115	2.46	2.73	61
	Average	2.97	3.93	199.55	1.17	1.17	105.00
	SE	0.42	0.70	19.54	0.20	0.23	10.25
Winter	M15	3.02	4.27	170	1.49	1.39	89
	M33	1.15	1.34	203	0.42	0.39	107
	M52	8.7	7.3	263	1.75	1.53	138
	M64	0.49	0.81	78	0.18	0.18	41
	M66	1.23	1.73	176	0.65	0.42	93
	M69	2.89	3.39	173	1.06	1.03	91
	M71	3.54	5.02	216	1.55	1.29	114
	M75	5.89	9.9	136	3.14	2.97	72
	Average	3.36	3.84	176.88	1.28	1.06	93.13
	SE	0.97	0.94	19.43	0.33	0.27	10.20

Table 3.3: Pairwise mean overlap area of neighboring 95% MCP home ranges. Values above the diagonal represent pairwise overlap area. Values below the diagonal represent the proportion of overlap area relative to home range area, given as a percentage. Dashes represent non-neighboring home ranges with no overlap.

FoxID	M15	M33	M48	M52	M64	M66	M69	M71	M72	M73	M75
M15		-	0.18	1.38	-	0.15	-	-	0.06	-	-
M33	-		0.38	-	0.09	-	-	-	-	-	-
M48	5.74%	13.54%		-	-	0.01	-	-	-	-	-
M52	28.27%	-	-		-	0.15	-	-	0.36	-	-
M64	-	6.36%	-	-		-	-	-	-	-	-
M66	7.30%	-	0.60%	4.87%	-		-	-	-	-	-
M69	-	-	-	-	-	-		-	-	-	-
M71	-	-	-	-	-	-	-		-	<0.01	0.06
M72	2.95%	-	-	11.78%	-	-	-	-		-	-
M73	-	-	-	-	-	-	-	0.08%	-		0.18
M75	-	-	-	-	-	-	-	1.25%	-	3.99%	

Table 3.4: Habitat composition of 95% KDI home ranges by area (km²) and percentage.

FoxID	Bare Area (%)	Chaparral Area (%)	Grassland Area (%)	Lupine Area (%)	Scrub Area (%)	Woodland Area (%)
M15	0.23 (6.5%)	0.00 (0.0%)	2.57 (72.5%)	0.22 (6.1%)	0.51 (14.3%)	0.02 (0.5%)
M33	0.24 (9.0%)	0.00 (0.0%)	0.97 (37.0%)	0.84 (31.9%)	0.58 (21.9%)	0.01 (0.2%)
M48	0.25 (6.6%)	0.00 (0.0%)	0.44 (11.6%)	3.05 (79.2%)	0.10 (2.7%)	0.00 (0.0%)
M52	0.24 (4.2%)	0.43 (7.6%)	3.32 (58.7%)	0.00 (0.0%)	1.50 (26.6%)	0.17 (3.0%)
M64	0.12 (15.8%)	0.00 (0.0%)	0.41 (51.7%)	0.00 (0.0%)	0.23 (29.5%)	0.02 (3.0%)
M66	0.07 (4.5%)	0.01 (0.4%)	1.33 (87.7%)	0.00 (0.0%)	0.11 (7.4%)	0.00 (0.0%)
M69	0.30 (6.6%)	0.23 (5.0%)	2.10 (46.2%)	0.00 (0.0%)	1.89 (41.7%)	0.02 (0.4%)
M71	0.16 (3.6%)	1.81 (40.4%)	1.77 (39.4%)	0.00 (0.0%)	0.47 (10.5%)	0.27 (6.0%)
M72	0.06 (3.6%)	0.00 (0.0%)	1.06 (67.7%)	0.00 (0.0%)	0.45 (28.7%)	0.00 (0.0%)
M73	0.35 (7.3%)	0.00 (0.0%)	3.67 (76.9%)	0.00 (0.0%)	0.75 (15.6%)	0.01 (0.2%)
M75	0.16 (1.9%)	1.83 (21.0%)	4.99 (57.3%)	0.00 (0.0%)	1.51 (17.3%)	0.21 (2.5%)
Avg	0.20 (6.3%)	0.39 (6.8%)	2.06 (55.2%)	0.37 (10.7%)	0.74 (19.7%)	0.07 (1.4%)
SE	0.03 (1.1%)	0.22 (3.9%)	0.44 (6.4%)	0.28 (7.4%)	0.19 (3.4%)	0.03 (0.6%)

Table 3.5: Pairwise mean overlap of neighboring 95% KDI home ranges. Values above the diagonal represent pairwise overlap area. Values below the diagonal represent the proportion of overlap area relative to home range volume, given as a percentage. Dashes represent non-neighboring home ranges with no overlap.

FoxID	M15	M33	M48	M52	M64	M66	M69	M71	M72	M73	M75
M15		-	0.16	0.63	-	0.27	-	-	0.36	-	-
M33	-		0.69	-	0.16	-	-	-	-	-	-
M48	2.75%	11.21%		-	-	0.19	-	-	-	-	-
M52	8.13%	-	-		-	0.20	-	-	0.33	-	-
M64	-	7.52%	-	-		-	-	-	-	-	-
M66	6.29%	-	4.78%	2.98%	-		-	-	-	-	-
M69	-	-	-	-	-	-		-	-	-	-
M71	-	-	-	-	-	-	-		-	0.12	0.65
M72	8.37%	-	-	5.70%	-	-	-	-		-	-
M73	-	-	-	-	-	-	-	2.11%	-		0.77
M75	-	-	-	-	-	-	-	6.38%	-	8.92%	

Table 3.6: Second order distance ratios by habitat for each fox. Ratios >1.0 indicate avoidance and ratios <1.0 indicate selection. To calculate average, raw values were natural log transformed, averaged, then exponentiated.

FoxID	Bare	Chaparral	Grassland	Lupine	Scrub	Woodland
M15	1.00	1.10	0.24	0.11	3.16	1.62
M33	1.21	1.83	1.54	0.07	1.34	2.21
M48	1.74	1.78	7.99	0.00	5.29	4.49
M52	0.93	0.58	0.36	0.46	0.67	0.53
M64	0.29	0.54	0.26	0.32	0.67	0.31
M66	1.10	1.08	0.03	0.17	2.61	1.72
M69	1.46	0.65	0.76	1.87	0.30	1.10
M71	1.21	0.20	1.50	0.95	1.17	0.30
M72	0.76	1.13	0.30	0.25	0.56	0.87
M73	0.50	2.18	0.12	1.35	0.68	0.79
M75	1.44	0.58	0.89	1.03	0.95	0.57
Average	0.96	0.88	0.48	0.26	1.12	0.95
SE	0.16	0.21	0.44	0.54	0.26	0.25

Table 3.7: Third order distance ratios by habitat for each fox. Ratios >1.0 indicate avoidance and ratios <1.0 indicate selection. Averages calculated as in Table 3.6.

FoxID	Bare	Chaparral	Grassland	Lupine	Scrub	Woodland
M15	0.93	1.03	0.67	0.85	1.14	1.09
M33	0.53	0.97	0.68	1.16	0.64	0.82
M48	1.25	1.19	0.89	0.39	1.22	0.95
M52	0.78	1.17	1.19	0.89	0.62	0.72
M64	1.18	0.82	1.87	1.03	0.65	0.90
M66	0.76	0.96	0.96	1.04	0.71	0.97
M69	1.00	0.94	0.83	0.99	0.80	0.89
M71	0.84	1.00	0.77	1.03	0.94	1.30
M72	1.13	0.93	1.02	1.01	1.07	0.96
M73	1.07	1.02	1.09	1.00	0.82	0.87
M75	1.11	0.84	1.48	0.99	0.89	0.88
Average	0.94	0.98	0.99	0.91	0.84	0.93
SE	0.08	0.04	0.10	0.09	0.07	0.05

Table 3.8: 95% KDI average distance ratios ($\pm$ SE) for habitat types by season. Averages calculated as in Table 3.6.

Season	Bare	Chaparral	Grassland	Lupine	Scrub	Woodland
Fall	0.88 $\pm$ 0.08	0.99 $\pm$ 0.06	0.95 $\pm$ 0.16	0.99 $\pm$ 0.03	0.78 $\pm$ 0.10	0.93 $\pm$ 0.04
Winter	0.95 $\pm$ 0.09	0.97 $\pm$ 0.05	0.86 $\pm$ 0.16	0.98 $\pm$ 0.02	0.77 $\pm$ 0.04	0.96 $\pm$ 0.07

Table 3.9: 95% KDI average distance ratios ($\pm$ SE) by habitat type within time of day categories. Averages based on back transformed natural log ratios. Bare and grass habitats had significant selection with time of day as a main effect.

Time of Day	Bare	Chaparral	Grassland	Lupine	Scrub	Woodland
Crepuscular	-0.06 $\pm$ 0.06	-0.04 $\pm$ 0.03	-0.03 $\pm$ 0.08	-0.08 $\pm$ 0.06	-0.22 $\pm$ 0.06	-0.06 $\pm$ 0.04
Day	0.06 $\pm$ 0.09	-0.04 $\pm$ 0.07	0.17 $\pm$ 0.15	-0.13 $\pm$ 0.10	-0.33 $\pm$ 0.16	-0.16 $\pm$ 0.06
Night	-0.20 $\pm$ 0.08	0.00 $\pm$ 0.04	-0.26 $\pm$ 0.06	-0.07 $\pm$ 0.09	-0.06 $\pm$ 0.07	-0.01 $\pm$ 0.06
P-value	0.005	0.49	0.005	0.365	0.126	0.058

Table 3.10: Topography composition of study area.

Topography	Area (km ²)	Percent
Valley	7.44	10.2%
Low Slope	10.66	14.7%
Mid Slope	34.59	47.6%
Steep Slope	14.58	20.1%
Ridge	5.37	7.4%

Table 3.11: Topographic composition of 95% KDI home ranges by area (km²) and percentage.

FoxID	Valley Area (%)	Low Slope Area (%)	Mid Slope Area (%)	Steep Slope Area (%)	Ridge Area (%)
M15	0.41 (11.5%)	0.53 (14.9%)	1.53 (43.2%)	0.90 (35.4%)	0.17 (4.9%)
M33	0.19 (7.3%)	0.32 (12.3%)	1.84 (70.1%)	0.23 (8.8%)	0.04 (1.5%)
M48	0.21 (5.6%)	0.35 (9.2%)	2.51 (65.2%)	0.65 (16.8%)	0.13 (3.3%)
M52	0.80 (14.1%)	0.57 (10.2%)	2.33 (41.3%)	1.52 (26.9%)	0.42 (7.5%)
M64	0.07 (8.9%)	0.10 (12.4%)	0.52 (65.7%)	0.08 (10.0%)	0.02 (3.1%)
M66	0.09 (5.7%)	0.16 (5.7%)	0.74 (49.0%)	0.36 (23.6%)	0.17 (10.9%)
M69	0.42 (9.4%)	0.69 (15.2%)	2.11 (46.6%)	0.97 (21.4%)	0.33 (7.3%)
M71	0.37 (8.4%)	0.57 (13.0%)	2.27 (51.1%)	0.81 (18.3%)	0.41 (9.2%)
M72	0.16 (10.4%)	0.16 (9.9%)	0.64 (40.6%)	0.53 (33.4%)	0.09 (5.6%)
M73	0.47 (9.8%)	0.86 (18.1%)	2.23 (46.8%)	0.81 (16.9%)	0.41 (8.5%)
M75	1.02 (11.7%)	1.31 (15.0%)	3.81 (43.8%)	1.83 (21.0%)	0.73 (8.4%)
Avg	0.38 (9.3%)	0.51 (12.8%)	1.87 (51.2%)	0.79 (20.2%)	0.27 (6.4%)
SE	0.09 (0.8%)	0.11 (0.8%)	0.29 (3.2%)	0.16 (2.2%)	0.07 (0.9%)

Table 3.12: Third order distance ratios by topography for each fox. Ratios >1.0 indicate avoidance and ratios <1.0 indicate selection. Averages based on back transformed natural log ratios.

FoxID	Valley	Low Slope	Mid Slope	Steep Slope	Ridge
M15	0.77	0.75	0.05	0.50	1.07
M33	1.10	1.08	0.46	2.03	2.08
M48	1.82	2.26	0.73	1.25	1.73
M52	0.68	0.90	1.19	0.69	0.94
M64	0.96	0.90	0.62	3.04	1.79
M66	1.26	1.44	1.29	0.71	0.81
M69	1.10	0.97	1.13	1.08	0.92
M71	1.24	1.00	0.90	0.92	0.90
M72	0.83	1.08	1.39	0.70	0.96
M73	1.00	0.86	0.99	0.97	0.90
M75	0.98	0.97	1.21	0.97	0.87
Average	1.03	1.06	0.72	1.02	1.11
SE	0.08	0.09	0.29	0.16	0.10

Table 3.13: MCP home range area and density data for each island. Multiple values are provided for SCL island due to habitat specific home range and density data. Astericks represent 100% MCP scaled down to 95% MCP, home range area is estimated size based on scaling.

Island	MCP Home Range	
	Area (km ²)	Density (km ²)
SMI ₁	1.18	6.64
SRI ₂	3.39	0.86
SCZ ₃	0.55	9.15
SCI ₄	1.05	3.36
SNI ₅	0.93	10.65
SCL-6*	0.33	15.23
SCL-GL ₆ *	0.47	2.9
SCL-GMDS ₆ *	0.31	4.1
SCL-RMDS ₆ *	0.40	11.3
SCL-SD ₆ *	0.11	42.6

1- San Miguel Island. Coonan et al. 2010

2- Santa Rosa Island. Drake 2013, Coonan et al. 2010

3- Santa Cruz Island. Roemer et al. 2001

4- Santa Catalina Island. J. King, unpublished data

5- San Nicholas Island. Powers 2009, Garcelon & Hudgens 2008

6- San Clemente Island. Sanchez 2012. Values are for island wide average, grassland (GL), gentle maritime desert scrub (GMDS), rugged gentle maritime scrub (RMDS), sand dune (SD).

FIGURES

Figure 3.1: 95% minimum convex polygon home ranges for individual foxes (ID number in yellow). White circles are locations where GPS collars were deployed on foxes (not all collars were recovered). M51 had no home range analysis due to a mortality shortly after collar deployment.

Fig. 3.2: Seasonal 95% MCP home ranges, with red representing Fall (Sept.-Dec.15, n=11) and blue representing Winter (Dec. 16-Mar. 30, n=8). There was no significant difference in seasonal home range size.

Fig. 3.3: 95% kernel density isopleth home ranges for individual foxes with 50% core areas represented by yellow grading into red or yellow grading into blue.

Fig. 3.4: 95% KDI home ranges merged with updated vegetation layer, legend indicates habitat categories.

Figure 3.5: Habitat composition of individual 95% KDI home ranges and average composition.

Figure 3.6: Second order habitat selection by Santa Rosa island foxes. Mean ($\pm$ SE) distance ratios were natural log transformed; ratios <0 indicate selection and ratios >0 indicate avoidance. There was significant second order selection for lupine habitat within the study area.

Figure 3.7: Third order habitat selection by season. Mean distance ratios were natural log transformed, ratios <0 indicate selection, ratios >0 indicate avoidance. Overall, habitat selection did not differ by season.

Figure 3.8: Third order habitat selection by time of day. Mean distance ratios ($\pm$ SE) were natural log transformed; ratios <0 indicate selection and ratios >0 indicate avoidance. There was significant selection of grass and bare habitats during the night indicated by asterisk.

Figure. 3.9: 95% kernel density isopleth home ranges merged with topographic composition layer, legend indicates topography categories.

Figure 3.10: Topographic composition of individual 95% KDI home ranges and average composition.

Figure 3.11: Third order topographic selection by island foxes. Mean distance ratios ($\pm$ SE) were natural log transformed; ratios <0 indicate selection and ratios >0 indicate avoidance. There was significant selection for valleys and avoidance of steep slopes within 95% KDI home ranges.

Figure 3.12: Relationship between island fox MCP home range area and population density for six of the Channel Island populations. San Clemente (SCL) island (open squares) has multiple data points due to habitat specific density values. Curve fit is exponential. Data and sources are defined in Table 3.13.

Literature Cited

- Aebischer, N.J., Robertson, P.A., & Kenward, R.E. (1993). Compositional analysis of habitat use from animal radio-tracking data. *Ecology*, 74, 1313-1325.
- ArcGIS Desktop (Producer). (2011). ESRI (Version 10) [Computer software]. Redlands, CA.
- Asa, C.S., Bauman, J.E., Coonan, T.J., & Gray, M.M. (2007). Evidence for induced estrus or ovulation in a canid, the island fox (*Urocyon littoralis*). *Journal of Mammalogy*, 88(2), 436-440.
- Baker, P.J., Funk, S.M., Harris, S., & White, P.C.L. (2000). Flexible spatial organization of urban foxes, *Vulpes vulpes*, before and during an outbreak of sarcoptic mang. *Animal Behaviour*, 59, 127-146.
- Beier, P. (1995). Dispersal of juvenile cougars in fragmented habitat. *Journal of Wildlife Management*, 59, 228-237.
- Beyer, D.E., Jr. & Haufler, J.B. (1994). Diurnal versus 24-hour sampling of habitat use. *Journal of Wildlife Management*, 74, 1911-1916.
- Blackie, H.M. (2010). Comparative performance of three lightweight global positioning system collars. *Journal of Wildlife Management*, 58, 178-180.
- Cain, J.W., Krausman, P.R., Jansen, & B.D., Morgart, J.R. (2005). Influence of topography and GPS fix interval on GPS performance. *Wildlife Society Bulletin*, 33, 926-934.
- Carlquist, S. J. (1974). *Island biology*. New York: Columbia University Press.

- Collins, P.W. (1982). *Origin and differentiation of the island fox: a study of evolution in insular populations*. Unpublished master's thesis, University of California, Santa Barbara.
- Conner, I.M. & Plowman, B.W. (2001). Using Euclidean distance to assess nonrandom habitat use. In Millspaugh, J. & Marzluff, J.M. (Eds.), *Radio Telemetry and Animal Populations* (pp. 275-290). San Diego, CA: Academic Press.
- Conner, L.M., Smith, M.D., & Burger, L.W. (2003). A comparison of distance-based and classification-based analyses of habitat use. *Ecology*, 84, 526-531.
- Coonan, T.J. (2003). *Recovery strategy for island foxes (Urocyon littoralis) on the northern Channel Islands*. Unpublished manuscript, Channel Islands National Park, Ventura, CA.
- Coonan, T.J. (2009). *Summary Report: Eleventh Annual Meeting Island Fox Working Group*. Unpublished manuscript, Channel Islands National Park, Ventura, CA.
- Coonan, T.J. (2010). *Summary Report: Twelfth Annual Meeting Island Fox Working Group*. Unpublished manuscript, Channel Islands National Park, Ventura, CA.
- Coonan, T.J., Schwemm, C.A., Roemer, G.W., Garcelon, D.K., & Munson, L. (2005). Decline of an island fox subspecies to near extinction. *The Southwestern Naturalist*, 50(1), 32-41.
- Coonan, T.J., Rutz, K. Garcelon, D.K., Latta, B.C., Gray, M.M., & Aschehoug, E.T. (2005b). Progress in island fox recovery efforts on the northern Channel Islands. *Proceedings of the Sixth California Island Symposium* (pp. 263-273). California: Arcata.

- Coonan, T.J., Schwemm, C.A., & Garcelon, D.K. (2010). *Decline and recovery of the island fox: a case study for population recovery*. New York: Cambridge University Press.
- Crooks, K.R. (1994). Demography and status of the island fox and the island spotted skunk on Santa Cruz Island, California. *The Southwestern Naturalist*, 39(3), 257-262.
- Crooks, K.R. & Van Vuren, D. (1996). Spatial organization of the island fox (*Urocyon littoralis*) on Santa Cruz Island, California. *Journal of Mammology*, 77, 801-806.
- D'Eon, R.G. (2003). Effects of a stationary GPS fix-rate bias on habitat selection analyses. *Journal of Wildlife Management*, 67, 858–863.
- D'Eon, R.G., Serrouya, R., Smith, G., & Kochanny, C.O. (2002). GPS radiotelemetry error and bias in mountainous terrain. *Wildlife Society Bulletin*, 30, 430-439.
- Dickson, B.G., Jenness, J.S., & Beier, P. (2005). Influence of vegetation, topography and roads on cougar movement in southern California. *Journal of Wildlife Management*, 69, 264-276.
- Donavan, T.M., Freeman, M., Abouelezz, H., Royar, K., Howard, A., & Mickey, R. (2011). Quantifying home range habitat requirements for bobcats (*Lynx rufus*) in Vermont, USA. *Biological Conservation*, 144, 2799-2809.
- Dussault, C., Ouellet, J.P., & Coutois, R. (2005). A comparison of distance-based and classification-based analyses of habitat use: comment. *Ecology*, 86, 3119-3125.
- Erlinge, S. Hoogenboom, I., Agrell, J., Nelson, J., Sandell, M. (1990). Density-related home range size and overlap in adult field voles (*Microtus agrestis*) in southern Sweden. *American Society of Mammologists*, 71, 597-603.

- Fausett, L.L. (1982). *Activity and movement patterns of the island fox, Urocyon littoralis*. Unpublished doctoral dissertation, University of California, Los Angeles.
- Frair, J. L., Fieberg, J., Hebblewhite, M., Cagnacci, F., DeCesare, N. & Pedrotti, L. (2010). Resolving issues of imprecise and habitat-biased locations in ecological analyses using GPS telemetry data. *Philosophical Transactions of the Royal Society*, 365, 2187–2200.
- Garshelis, D.L. (2000). Delusions in habitat evaluation: measuring use, selection, and importance. In Boitani, L., & Fuller, T.K. (Eds.). *Research techniques in animal ecology: controversies and consequences* (pp. 111-164). New York: Columbia University Press.
- Gittleman, J.L. & Harvey, P.H. (1982). Carnivore home range size, metabolic needs and ecology. *Behavioral Ecology and Sociobiology*, 10, 57-63.
- Gregory, N.C., Hudgens, B.R., & Garcelon, D.K. (2012). *San Clemente island fox (Urocyon littoralis clementae) monitoring and demography – 2011*. Unpublished manuscript, Institute for Wildlife Studies, Arcata, California.
- Harestad, A.S. & Bunnell, F.L. (1979). Home range and body weight – a reevaluation. *Ecology*, 60, 389-402.
- Harris, S.W., Cresswell, J., Forde, P.G., Trehwella, W.J., Woolard, T., & Wray, S. (1990). Home range analysis using radio-tracking data – a review of problems and techniques particularly as applied to the study of mammals. *Mammal Review*, 20, 97-123.
- Hebblewhite M. & Merrill, E.H. (2007). Multiscale wolf predation risk for elk: does migration reduce risk? *Oecologia*, 152, 377–387.

- Hixon, M.A. (1980). Food production and competitor density as the determinants of feeding territory size. *The American Naturalist*, 115, 510-530.
- Hudgens, B.R. & Garcelon, D.K. (2011). Induced changes in island fox (*Urocyon littoralis*) activity do not mitigate the extinction threat posed by a novel predator. *Oecologia*, 165, 699-705.
- Jenness, J. (Author). (2006). Topographic Position Index (tpi_jen.avx) extension for ArcView 3.x. [Computer Software]. Flagstaff, AZ.
- Johnson, D.H. (1980). The comparison of usage and availability measurements for evaluation of resource preference. *Ecology*, 61, 65-71.
- Johnson, C.J., Heard, D.C., & Parker, K.L. (2002). Expectations and realities of GPS animal location collars: results of three years in the field. *Wildlife Biology*, 8, 153-159.
- Kerston, B. & Marzluff, J. (2009). *Animal movement, home range and resource utilization function (RUF) analysis in ArcMap 9.x*. Seattle, WA: University of Washington, School of Forest Resources.
- Kjellander, P., Hewlson, A.J., Liberg, O., Angibault, J.M., Bideau, E., & Cargnelutti, B. (2004). Experimental evidence for density-dependence of home range size in roe deer (*Capreolus capreolus*): a comparison of two long-term studies. *Oecologia*, 139, 478-485.
- Kleinman, D.G., & Eisenberg, J.F. (1977). The usefulness of behavior studies in developing captive breeding programs for mammals. *International Zoo Yearbook* 17, 81-89.

- Latta, B.C., Driscoll, D.D., Linthicum, J.L., Jackman, R.E., & Doney, G. (2005). Capture and translocation of golden eagles from the California Channel Islands to mitigate depredation of endemic island foxes. In *Proceedings of the Sixth California Islands Symposium* (pp. 341-350). Arcata, CA: Institute for Wildlife Studies.
- Laughrin, L.L. (1977). *The Island Fox: A field study of its behavior and ecology*. Unpublished doctoral dissertation, University of California, Santa Barbara.
- Laughrin, L. L. (1980). Populations and status of the island fox. In *Proceedings of the California Islands: proceedings of a multidisciplinary symposium* (745-749). Santa Barbara, CA: Santa Barbara Museum of Natural History.
- Lewis, J.S., Rachlow, J.L., Garton, E.O., & Vierling, L.A. (2007). Effects of habitat on GPS collar performance using data screening to reduce location error. *Journal of Applied Ecology*, 44, 663-671.
- MacArthur, R.H., Diamond, J.M., & Karr, J.R. (1972). Density Compensation in Island Faunas. *Ecology*, 53, 330-342.
- MacDonald, D.W. (1983). The ecology of carnivore social behavior. *Nature*, 301, 103-117.
- Mattisson, J., Andren, H., Persson, J., & Segerstrom, P. (2010). Effects of species behavior on global positioning system collar fix rates. *Journal of Wildlife Management*, 74, 557-563.
- Minta, S.C. (1993). Use of spatio-temporal interaction statistics on badgers to test predictions of territorial polygyny theory. *Oecologia*, 96, 402-409.

- Moen, R., Pastor, J., Cohen, Y., & Schwartz, C.C. (1996). Effects of moose movement and habitat use on GPS collar performance. *Journal of Wildlife Management*, 60, 659–668
- Moore, C.M., Collins, P.W. (1995). *Urocyon littoralis*. *Mammalian Species*, 489, 1-7.
- Morrison, M.L., Marcot, B.C., & Mannan, R.W. (1998). *Wildlife-habitat Relationships*. Madison, WI: University of Wisconsin Press.
- Neu, C.W., Beyers, C.R., & Peek, J.M. (1974). A technique for analysis of utilization-availability data. *Journal of Wildlife Management*, 38, 541-545.
- Powell, R.A. (2000). Animal home ranges and territories and home range estimators. In Boitani, L. & Fuller, T.K. (Eds.). *Research techniques in animal ecology: controversies and consequences* (pp. 65-110). New York: Columbia University Press.
- Powers, R.M. (2009). *Social behavior measured by home range overlap in island foxes (Urocyon littoralis dickey)*. Unpublished master's thesis, San Francisco State University.
- Rick, T.C., Erlandson, J.M., Vellanoweth, R.L., Braje, T.J., Collins, P.W., Guthrie, D.A., & Stafford, T.W. (2009). The origins and antiquity of the island fox (*Urocyon littoralis*): AMS 14C dates from California's Channel Islands. *Quaternary Research*, 71, 91-93.
- Rodgers, A.R., Carr, A.P., Beyer, H.L., Smith, L., & Kie, J.G. (2007). *HRT: home range tools for ArcGIS. Version 1.1*. Thunder Bay, Ontario: Ontario Ministry of Natural Resources, Centre for Northern Forest Ecosystem Research.

- Roemer, G.W., Garcelon, D.K., Coonan, T.J., & Schwemm, C. (1994). The use of capture-recapture methods for estimating, monitoring, and conserving Island Fox populations. In *Fourth California Islands Symposium* (pp. 387-400). Santa Barbara, CA: Santa Barbara Museum of Natural History.
- Roemer, G.W. (1999). *The ecology and conservation of the island fox (Urocyon littoralis)*. Unpublished doctoral dissertation, University of California, Los Angeles.
- Roemer, G.W., Smith, D.A., Garcelon, D.K., & Wayne, R.K. (2001). The behavioural ecology of the island fox (*Urocyon littoralis*). *Journal of Zoology London*, 255, 1-14.
- Roemer, G.W., Coonan, T.J., Garcelon, D.K., Bascompte, J., & Laughrin, L. (2001b). Feral pigs facilitate hyperpredation by golden eagles and indirectly cause the decline of the island fox. *Animal Conservation*, 4, 307-318.
- Sanchez, J.N. (2012). Spatial ecology of disease spread in the island fox. Unpublished master's thesis, Humboldt State University, Arcata, CA.
- Schoenherr, A.A., Feldmeth, C.R., & Emerson, M.J. (1999). *Natural history of the islands of California*. Berkeley, CA: University of California Press.
- Scott, J.M., Goble, D.D., Wiens, J.A., Wilcove, D.S., Bean, M. & Male, T. (2005). Recovery of imperiled species under the Endangered Species Act: the need for a new approach. *Frontiers in Ecology and the Environment*, 3, 383-389.
- Sharpe, P.B. & Garcelon, D.K. (2005). Restoring and monitoring bald eagles in southern California: the legacy of DDT. In *Proceedings of Sixth California Islands Symposium* (pp. 323-330). Arcata, CA: Institute for Wildlife Studies.

- Spatial Ecology LLC (Producer). (2011). Geospatial Modeling Environment (Version 0.5.5) [Computer Software]. Toronto, ON.
- Stalmaster, M.V. (1987). *The Bald Eagle* (Vol. 381). New York: Universe Books.
- Stamps, J.A. & Buechner, M. (1985). The territorial defense hypothesis and the ecology of insular vertebrates. *Quarterly Review of Biology*, 60, 155-181.
- State of California Natural Resources Agency Department of Fish and Game Wildlife Branch. (2011a). *Resource exploitation by island foxes: Implications for conservation*. San Diego, CA: Cypher, B.L., Madrid, A.Y., Van Horn Job, C.L., Kelly, E., Harrison, S.W.R., & Westall, T.L.
- State of California Natural Resources Agency Department of Fish and Game Wildlife Branch. (2011b). *Evaluation of new telemetry technologies for research on island foxes*. San Diego, CA: Cypher, B.L., Drake, E.M., Savage, J.A., Ralls, K., Coonan, T.J., & Perrine, J.D.
- Swarts, H.M., Crook, K.R., Willits, N., & Woodrooffe, R. (2009). Possible contemporary evolution in an endangered species, the Santa Cruz Island fox. *Animal Conservation*, 12, 120-127.
- Szor, G., Berteaux, D., & Gauthier, G. (2008). Finding the right home: distribution of food resources and terrain characteristics influence selection of denning sites and reproductive dens in arctic foxes. *Polar Biology*, 31, 351-362.
- Timm, S.F., Stokely, J.M., Gehr, T.B., Peebles, R.L., & Garcelon, D.K. (2000). *Investigation into the decline of island foxes on Santa Catalina Island*. Santa Catalina Island, CA: Santa Catalina Island Conservancy, Ecological Restoration Department.

- Trewhella, W.J., Harris, S., & McAllister, F.E. (1988). Dispersal distance, home range size and population density in the red fox (*Vulpes vulpes*): a quantitative analysis. *Journal of Applied Ecology*, 25, 423-434.
- United States Fish and Wildlife Service. (2007a). *A population monitoring framework for five subspecies of island fox (Urocyon littoralis)*. Ventura, CA: Ruben, E.S., Bakker, V.J., & Efford, M.G.
- United States Fish and Wildlife Service. (2007b). *Draft recovery plan for four subspecies of island fox (Urocyon littoralis)*. Ventura, CA: Island Fox Recovery Coordination Group.
- United States Fish and Wildlife Service (2004). Endangered and threatened wildlife and plants: listing the San Miguel Island Fox, Santa Rosa Island Fox, Santa Cruz Island Fox, and Santa Catalina Island Fox as endangered. *Federal Register*, 69(44), 10335-10353.
- Wayne, R.K., George, S.B., Gilbert, D., Collins, P.W., Kovach, S.D., Girmant, D., & Lehman, N. (1991). A morphological and genetic study of the island fox, *Urocyon littoralis*. *Evolution*, 45, 1849-1868.
- White, G.C. & Garrott, R.A. (1990). *Analysis of wildlife radio-tracking data*. San Diego, CA: Academic Press.
- Zimmerman, J.W. & Powell, R.A. (1995). Radiotelemetry error: location error method compared with error polygons and confidence ellipses. *Canadian Journal of Zoology*, 73, 1123-1133.

APPENDIX 1

Figure A1.1: Collar deployment data range and fox reproductive biology information.

Figure A1.2: Trapping grids and line transects with individual trap locations for Santa Rosa Island.

Fig. A1.3: Trap locations for GPS collar deployment on individual foxes on Santa Rosa Island 2009.

Fig. A1.4: Recovered GPS location data for individual foxes on Santa Rosa Island from September 2009 to June 2010.

APPENDIX 2

HABITAT TYPE MAPPING ON SANTA ROSA ISLAND THROUGH IMAGE CLASSIFICATION

Russell White

Purpose

A suitable depiction of habitat types within the study area was needed in order to perform habitat use analysis of the GPS-tracked foxes. Habitat types were defined based on vegetation communities of grassland, scrub, lupine scrub, chaparral, woodland and bare ground. Given the accuracy of GPS fox location and the patchy distribution of vegetation in the study area, accurate mapping of habitat boundaries was important to the relevance of the analysis. Existing vegetation datasets for Santa Rosa Island (Figure 1) were reviewed, though considered insufficient due to either poor spatial representation, or incomplete coverage of the study area. To provide a more complete, current and accurate vegetation layer for this study, an interactive supervised image classification method was undertaken using ESRI ArcGIS 10 with input data of color infrared imagery and LiDAR for Santa Rosa Island.

Figure A2.1. Previously existing vegetation layers for Santa Rosa Island (a.) digitized from 1988 aerial photos and (b.) digitized from 2009 imagery.

Data Preparation

The primary input for the classification process was the 2009 one meter resolution four-band imagery from the National Agricultural Imagery Program (NAIP) (<http://atlas.ca.gov/>). Individual quarter-quad tiles for Santa Rosa Island were downloaded and stitched into a single four-band TIFF image using the Mosaic to New Raster tool in ESRI ArcGIS. The imagery was inspected for proper georeferencing relative to other imagery and GIS layers. Other characteristics of the imagery were evaluated such as the presence of shadows, contrast between different vegetation types, and color consistency across the study area. Generally, positioning of the imagery was good, habitat types were discernible, topographic shadowing was moderate, and color tone was consistent for most of the study area.

The second input used in the classification process was the 2010 ARRA LiDAR data available through the USGS Center for LiDAR Information and Research (CLICK) (<http://lidar.cr.usgs.gov/>). The entire LiDAR collection for the island was downloaded in LAS format. This dataset contained a very dense collection of elevation points (three to seven points per square meter). More information regarding the flight and sensor parameters of this collection are available from the 2011 Coastal GeoTools Conference, presentation A09 (<http://geotools.csc.noaa.gov/program/default.aspx>). LiDAR data had been classified into ground and non-ground points by the original data vendor. Ground points were gridded into a 1 m DEM using Natural Neighbor interpolation in the Terrains toolset of ArcGIS 10. A corresponding digital surface model (DSM) was generated using

first return LiDAR points to represent the top-of-vegetation elevation for the study area. This layer was produced using the CanopyModel command in the USFS Fusion software, a free LiDAR processing toolset developed by the USFS Remote Sensing Applications Center (<http://www.fs.fed.us/eng/rsac/fusion/>). Finally, a Canopy Height Model (CHM), representing the height of vegetation from the ground, was created by subtracting DEM elevations from the DSM. This was calculated using the Raster Calculator in ArcGIS 10.

Figure A2.2. (a) NAIP imagery, (b) DEM hillshade, (c) DSM hillshade, (d) LiDAR Canopy Height Model (CHM).

The combination of imagery and LiDAR heights appeared sufficient to distinguish the given habitat types, so a workflow was developed to outline the steps required to produce a final habitat type layer (Figure 3).

Figure A2.3. Image classification workflow.

Interactive Supervised Image Classification

The Image Classification Toolbar in ArcGIS 10 contains tools for supervised and unsupervised classification of multi-band imagery. Supervised classification was used in order to target the specific habitat categories established for the study. A series of small training polygons were digitized across the study area to represent examples of each habitat type (Figure 4a). When polygons were completed, the classification was performed to produce an initial classification result. Depending on the quality of results, training polygons were added or removed to guide the next iteration of the classification. Initial results of the classification were promising, but additional intervention was required to correctly classify the desired habitat types. For the purposes of this study, scrub and chaparral were separated, but other sparse vegetation, such as baccharis scrub and riparian vegetation were simply designated into the scrub category. Therefore, any vegetation falling outside of chaparral areas were re-classified into the scrub category.

Fortunately, on Santa Rosa Island, the chaparral areas form distinct units which could be easily identified and maintained as chaparral.

Figure A2.4. Classification training polygons (a), and initial classification results (b).

Woodland Classification using LiDAR Canopy Height Threshold

Using the infrared imagery alone, chaparral and woodland habitat types could not be easily separated. These areas were often adjacent and shared similar color and texture characteristics. In addition, woodland cover was often located on steep and heavily shadowed slopes, causing confusion of the classifier. In early attempts, shadowed areas were often mis-classified as woodland cover. An alternative approach to classifying woodland vegetation became possible with the release of the 2010 LiDAR point data for the Channel Islands. With a one meter resolution LiDAR canopy height model, a simple vertical threshold was used to designate woodland cover. The specific height threshold of four meters was determined through visual inspection and input from the NPS botanist familiar with the study area.

Figure A2.5. Woodland cover mapped using LiDAR height threshold (a), and integrated into existing raster classification (b)

Raster Generalization, Vectorization and Clean-up

As a pixel classifier operating on one meter resolution imagery, the classification result was often speckled and required smoothing or generalization before conversion to a polygon layer. This condition was especially true in areas of sparse and patchy vegetation, such as the grassland-scrub encountered in the study area. An automated tool was developed using the ArcGIS Model Builder to perform generalization on the classified raster (Figure 6). This approach used a Focal Majority filter on a 5 m x 5 m moving window to re-assign classification values to the majority value found within the neighborhood. An intermediate step of resampling was necessary to fill Null values for cases where there was no majority value in the 5 m window. Finally, the ArcGIS Boundary Clean tool was used to further refine the boundaries between habitat types.

Figure A2.6. ArcGIS model for raster generalization.

The generalized raster was then converted to a polygon layer using the ArcGIS tool Raster to Polygon. The command Eliminate was used to delete small outlying patches of vegetation (area less than 1000 m²). Figure 7 below illustrates the process from original image (a), to classified image (b), generalization and conversion to polygon (c), and finally removal of small isolated patches (d).

Figure A2.7. Image classification, generalization and clean-up. Original image (a), classified raster (b), raster generalization and conversion to polygon (c), final polygon layer (d).

Discussion

Six habitat types based on vegetation community were mapped using semi-automated image classification and generalization for a 95 km² study area on Santa Rosa Island.

The combination of high resolution color infrared imagery, LiDAR point data, and image classification tools in ArcGIS 10 provided an alternative to traditional photo

interpretation and manual digitizing. This approach was developed as a trial to evaluate the strengths and weakness of applying the available tools and datasets.

In general, the classification was effective in identifying homogenous patches of vegetation, such as the open grassland, bare ground and dense coastal scrub. Areas of sparse vegetation, such as the open scrub and grassland, presented greater challenges. An image analyst would likely group patchy vegetation into a common class, and it was difficult to achieve similar grouping through the pixel-based classification and neighborhood smoothing. Topographic shading and shadows presented another challenge, due to the rugged terrain and timing of the flight. Shadowed areas were often grassland or bare ground, but were classified as scrub. This type of misclassification illustrates the need for careful visual inspection, review and editing of the classified layers. While many steps of this process can be automated, substantial review and manual editing was needed to refine the layer into a common, consistent output. Overall, it was worthwhile to investigate these remote sensing approaches as datasets and software tools become more readily accessible. It is unlikely that automated approaches will wholly replace traditional photo interpretation, but there are scenarios where a remote sensing approach can efficiently supplement existing mapping efforts.