4 A Monitoring Plan for San Miguel Island Foxes

San Miguel Island, with an area of 36 km^2, is the smallest Channel Island inhabited by foxes (Map 4-1). It lies 42 km (26 miles) from the mainland, and is the most northern and western of the Channel Islands (Schoenherr et al. 1999, Map 1-1). This results in San Miguel Island having one of the windiest, foggiest, and most maritime climates of all the Channel Islands (Schoenherr et al. 1999). Its topography is relatively gentle compared to other northern Channel Islands, with most of the island comprising a large plateau with two rounded peaks─San Miguel Hill and Green Mountain. Steep bluffs line the coast, especially along the southern shoreline.

The island is owned by the U.S. Navy, but is managed by the National Park Service (NPS, Coonan 2003) and open to the public which arrives primarily by private or public boat. However, with the exception of Cuyler Harbor, most of the shoreline is closed to the public, and public access beyond the ranger station is restricted unless hikers are accompanied by a ranger. There are no roads or motorized vehicles on the island, and the only means of travel is by a set of walking trails that bisects the island north-south and east-west. Developed areas are limited to a ranger station, an airstrip, and a research facility.

The current vegetation consists primarily of grassland (34.8% of the island), *Haplopappus* scrub (29.9%), beach and coastal dunes (14.7%), and unstabilized dune (11.8%; Map 4-2). This vegetation is likely the result of many years of overgrazing by introduced livestock and erosion caused by loss of vegetation (Schoenherr et al. 1999). Remains of ancient trees in the caliche forests, most likely from the late Pleistocene, hint at a very different historical vegetation composition (Schoenherr et al. 1999). There are several freshwater springs on the island. San Miguel Island provides important habitat for a variety of land and seabirds including the endemic San Miguel Island song sparrow (*Melospiza melodia micronyx*), Brandt's cormorants (*Phalacrocorax penicillatus*), and Cassin's auklets (*Ptychoramphus aleuticus*). In addition, the island supports some of the world's largest rookeries for California sea lions (*Zalophus californianus*) and northern elephant seals (*Mirounga angustirostris*; Schoenherr et al. 1999).

4.1 San Miguel Island Foxes

Island foxes were first described on San Miguel Island in 1857 (Laughrin 1971) and are classified as an endemic subspecies (*Urocyon littoralis littoralis*; Moore and Collins 1995). Based on field work conducted in 1971, Laughrin (1973, 1980) reported that foxes on San Miguel Island appeared to be "abundant," that this population was at higher densities than those on Santa Catalina and San Nicolas islands, and that vegetation was in a state of recovery after many years of livestock grazing. In the late 1970s the population was also reported to be stable and estimated at 151-498 animals (Collins and Laughrin 1979).

However, field work during the 1990s documented a rapid decline in the population, with an estimated loss of over 90% between 1995 and 2000 (Roemer et al. 2004). The population decreased from a high of 450 adults in 1994 to 15 foxes in 1999, 14 of which were taken into captive breeding facilities established on the island in 1999 (Coonan 2003, Coonan et al. 2005).

Predation by golden eagles appeared to be the primary cause of death among radiocollared foxes, although high parasite loads, observed in two dead foxes not killed by golden eagles, may have impaired reproduction (Coonan et al. 2005). The decline on San Miguel Island was simultaneous with a similar decline on Santa Cruz Island and an inferred decline on Santa Rosa Island, which were also attributed to predation by golden eagles, which were supported in part by exotic livestock (Roemer et al. 2002a).

Golden eagles are believed to have first colonized the northern Channel Islands in the early 1990s, with the first reported sightings in 1993 (Roemer 1999, Roemer et al. 2001b, Latta 2005). Golden eagle sightings increased in the northern islands during 1993-1998, as did fox predation by golden eagles (Coonan et al. 2005). In contrast, fox populations on the southern Channel Islands (San Nicolas, San Clemente, and Santa Catalina) did not experience predation by golden eagles and did not decline precipitously during this time period, but rather remained relatively stable except for an apparent gradual decline on San Clemente Island over a 10-year period (Roemer et al 2001b). An ongoing collaborative effort by the NPS and The Nature Conservancy (TNC) has since been initiated in an attempt to rid the northern Channel Islands of resident golden eagles (S. Morrison, TNC, pers. comm.).

It is likely that human activities promoted the presence of golden eagles on the northern Channel Islands. First, the introduction of livestock may have provided additional food sources (via presence of young animals or carrion). For example, on Santa Cruz Island, golden eagles had opportunities to feed on feral pigs in the form of young animals and carrion (Roemer 1999). A simulation model suggested that the fox population alone could not have supported the number of eagles observed on Santa Cruz Island over an extended time period, leading the authors to conclude that the presence of feral pigs was subsidizing a predator and that it had contributed to the decline of the fox populations on the northern islands (Roemer et al. 2001b). Pigs were introduced to the Channel Islands in the 1850s (Junak et al. 1995) and have been on Santa Cruz Island since at least the 1920s (Van Vuren 1984). Second, the extirpation of bald eagles (*Haliaeetus leucocephalus*) due to organochlorine contamination by the late 1950s (Kiff 1980) may have removed an effective competitor of, or deterrent to, golden eagles. In recent years, NPS and IWS appear to have succeeded in reestablishing a bald eagle population on the northern Channel Islands, and TNC and NPS have recently reported apparent success in eradicating pigs from Santa Cruz Island (Morrison et al. 2007) and most golden eagles from the islands. However, the nonnative deer and elk herds on Santa Rosa Island are not scheduled to be removed until 2011, and those populations perpetuate an elevated risk to fox viability on all of the northern islands by subsidizing golden eagles with a food source.

The risk of eagle predation has likely increased on all of the Channel Islands due to loss of vegetation cover from years of over-grazing by feral livestock and introduced ungulates (Roemer 1999, Roemer et al. 2001b). On San Miguel Island, domestic sheep grazing helped convert much of the island's shrub vegetation to alien annual grasslands (Schoenherr et al. 1999, Coonan et al. 2005), and many of the ravines that cut across the island are a result of erosion resulting from years of extensive livestock grazing, military bomb testing, and agriculture; activities that no longer exist on the island (Schoenherr et al. 1999). Domestic sheep were grazed on the island since approximately 1850, with 6,000 sheep reported to be on the island in 1862 (Hochberg et al.

1979, cited in Schwemm and Coonan 2001). By 1971, most livestock had been removed from the island, with the last burros removed in 1978 (Laughrin 1973, Schwemm and Coonan 2001).

Although no large-scale disease die-off has been reported for foxes on San Miguel Island, disease remains a real threat to all island foxes, as demonstrated by the near extirpation of Santa Catalina Island foxes, because their isolation on islands has minimized or prevented their exposure to diseases. In addition, the low genetic diversity observed among island foxes increases their susceptibility to novel diseases (Wayne et al. 1991). For this reason, introduction of novel diseases, particularly those carried by dogs and other animals brought to the island by humans, presents a constant and serious risk. To explore the possibility that the population decline observed in the mid-1990s was caused by disease, foxes were tested for five potentially lethal diseases and checked for heartworm antigens and the presence of parasites, and these results were compared to disease profiles from 1988 (Roemer et al. 2000, Roemer et al. 2001b). According to Roemer et al. (2001b), there was no concordance between pathogen prevalence and the temporal and geographic pattern of population decline. No evidence of exposure to canine distemper virus was found in any of the five subpopulations sampled, and parvovirus antibodies decreased between the two sampling periods. Canine heartworm (*Dirofilaria immitis*) was suspected to be a potential threat to island foxes, and positive *Dirofilaria* antigen tests were documented in samples from four of the six populations (San Miguel, Santa Rosa, Santa Cruz, and San Nicolas) collected in 1988 and during 1997-1998 (Roemer et al. 2000). Despite the apparently high antigen seroprevalence (58-100% in 1997-1998), necropsy of over 400 island foxes from all islands has found no evidence of heartworm nor heartworm disease (L. Munson, UC Davis, unpublished data). Therefore, the antigen test results are now suspected to be false positives, possibly detecting another antigen present in fox serum (Coonan et al. 2005, Bakker et al. 2006). Other evidence also suggests that heartworm infection did not contribute to the observed population declines. The seroprevalence measured on San Nicolas Island, where the fox population was stable and dense, was higher than on Santa Cruz Island, where the population was decreasing at the time of the study (Roemer et al. 2000, Roemer et al. 2001b). In addition, the heartworm test detected antigens in all four populations in or before 1988, pre-dating the population declines. Finally, seroprevalence in the San Miguel Island population was high in 1994, when densities on that island reached the highest levels ever recorded.

Foxes on San Miguel Island currently experience little human impact compared to foxes on other islands. Since the 1940s, no permanent residents have lived on the island except for NPS staff, and current rules limit visitor access to most of the island unless they are accompanied by NPS staff (Schoenherr et al. 1999). However, shipwrecks and unauthorized visits do occur.

With the assistance of a captive breeding program and an on-going effort to remove golden eagles from the northern Channel Islands, fox populations on San Miguel Island have increased from near extinction in 1999. The first animals to be returned to the wild were released from captivity in 2004, and current population numbers are approximately 80 animals in the wild and 32 animals in captivity (Coonan and Dennis 2006, T. Coonan, NPS, pers. comm.).

4.2 Monitoring Objectives

The following monitoring objectives were identified for San Miguel Island (Section 2.1):

Parameters for tracking recovery

- Annual estimate of island-wide population size, with an 80% confidence interval. The point estimate should have a coefficient of variation (CV) of ≤20%.
- Estimate of total and cause-specific annual mortality rates. Mortality monitoring should be sufficient to detect an annual rate of eagle predation of 2.5% or greater, averaged over 3 years. In addition, these data should provide a means of surveying for disease and facilitate health research.
- Trend in population size estimated either from annual abundance estimates or from population models. This estimate has no targeted precision; rather the precision of the trend estimate will be determined by the precision of the population estimates and possibly by precision of mortality rates.

Parameters for island-specific management decisions

- Cause-specific mortality rates by age and sex, considering all causes of mortality.
- Reproduction measured in terms of annual recruitment (i.e., inclusive of pup survival).
- Disease and health profiles, as sampled from all deceased foxes and from a subset of the living population based on sampling protocols determined by the Fox Health TEG.

4.3 Past and Current Monitoring

4.3.1 Summary of Past and Current Protocols

The earliest quantitative study of San Miguel Island foxes was conducted in October 1971 (Laughrin 1973). Traps were set along two transects at 160-meter (0.1-mile) spacing. Traps were set for 3 nights total, and transects were moved each day to sample a variety of habitats, primarily in coastal sage scrub and grassland-iceplant associations (Laughrin 1980). Density was estimated by assuming that each line trapped an area 800 meters (0.5 mile) wide, based on average distance of movement among trapped foxes on San Clemente Island (Laughrin 1973). An initial attempt was made to extrapolate this value across the entire island to generate an island-wide population estimate but, due to the "unreliability of density estimates and inappropriateness of applying these estimates to the entire island, a determination of population size was abandoned" (Laughrin 1973). In addition, the island was searched for fox sign. This study provided data on trap success, age structure, general health and body condition, and diet composition, in addition to observations of 30 foxes on the island (Laughrin 1973). The author recommended that future researchers should trap the five islands as close in time as possible, sample more of various habitat types, and employ repeated sampling (Laughrin 1973).

In 1993, Roemer et al. (1994) initiated a study to evaluate population density and size on San Miguel Island. Two grids, with dimensions of 6x7 and 7x7 traps and an inter-trap distance of

250 meters, were established in areas of mixed habitat, including grassland, *Haplopappus* scrub, coastal sage scrub, and coastal dune scrub. Areas that were severely altered by human activities or too steep or rugged to access were avoided. Trapping was conducted annually (at varying times during July-September), and trapping occurred for 6 consecutive days, with traps checked every 24 hours (Coonan et al. 2005). Animals were tagged with a passive integrated transponder (PIT) tag. In addition to grid-specific density and abundance estimates, this study provided data on age structure, sex ratios, general health and body condition, and an index of reproduction.

Population size was estimated for each grid using the program CAPTURE (White et al. 1982) and Chapman's modification of the Lincoln-Petersen method (Seber 1982). Chapman's modification was used as a comparison method because model selection in the program CAPTURE may not be robust with small sample sizes (Roemer et al. 1994). For the Lincoln-Petersen method, animals captured during the first 3 days were "marked," and the last 3-4 days were considered the recapture period. Density was estimated from $D = N/A_w$ where A_w is the effective trapping area obtained by adding a boundary strip of width W to the area of the grid, with W estimated as half the mean maximum distance moved (MMDM) between traps (Dice 1938, Wilson and Anderson 1985). An island-wide population estimate was generated by extrapolating grid-specific density estimates to the entire island. The composition of various vegetation types (referred to as habitat types in Roemer et al. 1994) on each grid was compared to the composition of corresponding vegetation types on the island, and "…fox density from each grid was then multiplied by the appropriate habitat area for each island, yielding an estimate of the number of adults." Areas not judged to support foxes, such as urban, barren, and cultivated areas, were omitted from the calculations (Roemer et al. 1994).

The two grids described above were trapped annually during 1993-1999, and a third grid was added and trapped annually during 1994-1999 (Coonan et al. 2005). In 1999, 17 remote automated cameras were used to augment population estimates from annual trapping. Chapman's modification of the Lincoln-Petersen estimator was used to estimate population size, using re-sighted animals, many of which were radiocollared and could therefore be identified (Coonan et al. 2005). Trap data and open population models in program MARK (White and Burnham 1999) were used to estimate annual apparent survival and 15 foxes were radiocollared in November 1998 to examine causes of mortality and to provide an additional estimate of survival (Coonan et al. 2005). Radiocollared foxes were monitored daily for 12 months or until they were removed for captive breeding by the end of 1999 (Coonan et al. 2005).

In addition to the above trapping effort, foxes were trapped in 1998 along transects on San Miguel Island and the other five other islands inhabited by island foxes, as part of a cross-island comparison of density (Roemer 1999). Traps were set approximately 200 meters apart, and were set for 6 nights for a total of 76 trap-nights. Trap results were presented as trap success, which was compared across islands to determine if populations on the six islands were showing the same abundance trends.

By 1999, all but one of the remaining foxes had been brought into captivity (the last wild fox was brought into captivity in 2003), so trapping was discontinued during 2000-2005 (Coonan et al. 2004, Coonan and Dennis 2006). The first captives were returned to the wild in 2004. All released animals were radiocollared and monitored for survival for up to one year following release. Survival of collared animals was estimated using the Kaplan-Meier procedure with staggered entry (Pollock et al. 1989, Coonan and Dennis 2006). All mortalities were investigated, and fox carcasses were submitted for necropsy at UC Davis. Automated cameras were set up near den sites to monitor the numbers of pups in wild litters. Additionally, focused trapping around trap sites was used to replace collars or to insert PIT tags into wild-born pups. This generated data on health, body condition, relative abundance in various parts of the islands (measured as trap success), an index of reproduction, age structure, and sex ratios.

In 2006, a new set of four smaller (6 x 3 traps) grids were established along hiking trails on the island. The center row of six traps followed along the trail, with a row of six traps on either side, with inter-trap spacing of approximately 200 meters. Traps were set for 4 consecutive nights. Densities for these smaller grids were estimated using program DENSITY (Efford 2004, Efford et al. 2004). The primary reason for not resuming trapping of grids used in 1993-1999 was a lack of personnel to trap the larger grids.

4.3.2 Representation Analysis of Current Trapping Protocols

To determine how well existing trapping protocols represent habitat variability on the island, we conducted representation analyses using both univariate and multivariate techniques (Appendices A and F). Although we examined only the most recent (current) trapping protocols for other islands, we included an analysis of grids trapped during 1993-1998 on San Miguel Island, because this was the established protocol until the remaining foxes were removed from the wild (due to threat of golden eagle predation), and the 2006 protocol was only recently established and designed primarily in light of limited personnel availability.

Based on univariate analysis, grids trapped during 1993-1998 and those trapped in 2006 both differed statistically from island representation in terms of the parameters measured (Appendix A). In general, both trapping protocols sampled areas that were less steep, less rugged, farther from the shoreline, and closer to trails and developed areas than island-wide areas (Maps 4-3 and 4-4). In addition trapped areas were closer to drainages and ravines (represented by the CDFG hydrology layer as an index to potential freshwater on this island) under both protocols. Some of these differences may not be biologically relevant, as some differences in the two datasets were small relative to documented fox movement patterns (e.g., distance to freshwater) or were not considered relevant given the small absolute difference (e.g., slope and ruggedness; Appendix A). Both protocols failed to sample major vegetation types in proportion to availability, and this was due primarily to over-sampling of grassland and under-sampling of beach and coastal dunes as well as unstabilized dunes (Map 4-2).

In general, based on the univariate analysis, grids trapped during the 1990s represent the island more adequately. This is likely due to a larger percentage of the island being sampled in the 1990s (49%) than in 2006 (37%) but may also be influenced by grid placement. All parameters are more adequately represented by the 1993-1998 grids except for distance to developed areas, which differs more from island-wide areas when 1993-1998 grids are used than when 2006 grids are used. This may be because 2006 grids were more evenly spaced between the two centers of developed areas. In terms of vegetation representation, 1993-1998 grids sampled vegetation variation on the island more adequately.

We also examined habitat representation of both the trapping scenarios using a multivariate approach. We performed a principal components analysis (PCA) for key habitat attributes and compared mean principal component (PC) scores for trapped areas to those of the entire island (Appendix F). Both former and current grid trapping locations substantially under-represent (a) steep rugged shoreline far from trails, and (b) habitat far from drainages and development, such as on the northern and western peninsulas. Sixty percent (60%) of the variation in habitat attributes is captured by these two multivariate habitat types, and trapped areas show the most significant biases in habitat representation for these types. To a lesser extent, existing grid locations also under-represent areas far from development, regardless of proximity to trails or drainages, and over-represent interior areas.

Individual grids generally match overall patterns of representation. Old and new grids sample relatively similar habitat attributes although old grids span a somewhat wider range of habitat types, as also suggested by univariate analyses. When examining habitat attributes by vegetation type, both old and new grids again generally mirror overall patterns of representation, although the beach and coastal dune habitat sampled in current grid locations is misrepresentative of the island as a whole.

4.3.3 The Ability of Existing Protocols to Meet Current Objectives

Previous and ongoing studies of island foxes on San Miguel Island have produced a wealth of information on population trends, estimates of density, age structure and sex ratios, animal health, and causes of mortality. This section discusses the adequacy of existing protocols to address current monitoring objectives (Section 4.2). We recognize that previous field protocols may not have been designed to address the same set of objectives. Our summary is intended to indicate where refinements can be made to better address current monitoring objectives, rather than to critique previous study designs.

Population size

The ability to use trapping grids has been a great advantage for fox monitoring on San Miguel Island, as grid trapping can provide relatively robust grid-specific estimates of abundance and density. In addition, the current four grids represent a fairly large proportion of the island's area. Assuming a 600-meter effective trap radius (an approximation based on the mean of the mean maximum distances moved for each trapping session for all years for grids on San Clemente, Santa Cruz, San Miguel, and San Nicolas islands; V. Bakker, unpublished data), the four grids collectively sample approximately 37% of the island. Although grids represent a variety of vegetation types, they tend to over-sample grasslands and under-represent beach and coastal dune and unstabilized dune areas. Grids used during 1993-1999, most likely due to their larger size, represented vegetation on the island more adequately (Section 4.3.2, Appendices A and F).

Other features such as ruggedness, slope, or distance to shoreline may also influence fox densities. Our representation analyses indicate that the current grids tend to under-represent areas near the shoreline and further from trails and developed areas. Although it is probably not feasible to sample the complete habitat variability of San Miguel Island with grid sampling, partly because this would assume the ability to identify and measure all habitat attributes important to foxes, it may be possible to increase representation of the island by dispersing grids more widely across the island, ideally involving a randomized method of distributing trap effort.

Existing (2006) grids are also expected to provide low precision in their estimate of density. When the existing grid layout was evaluated by simulation, assuming that grids were independent, precision of the density estimate, CV($\hat{D}$), was 38-64%, which is much less precise than the targeted CV of 20% (Appendix K). In addition, the current grids are very close to each other; therefore, movement of animals between grids is likely, especially as the grids are not trapped simultaneously. This likelihood of movement between grids must be incorporated into models for estimating density.

Trends in population abundance or density

Standardized grids provide an effective way to track trends in abundance or density in the vicinity of each sample grid. Whether or not these grid-specific estimates of trends can be extrapolated to the entire island depends on how well the grids represent the island. Given that the current grids sample 37% of this small island, it may be possible to infer general population trends, especially if all four grids exhibit similar patterns; however, it is also possible that habitats not represented by the grids could be experiencing different trends than sampled areas.

Several aspects of the trapping protocols could be further standardized to increase accuracy and precision of trend estimates.

1. The same grids have not been trapped across all years. Grids trapped during 1993-1999 allowed inter-annual comparison of parameters such as density, or possibly trap success. A switch to new grids in 2006, which we recognize was due in great part due to fiscal constraints, interrupted the continuity of data. Nevertheless, if the new grids are continued with a standardized protocol (e.g., same trap locations every year), data obtained could be used to track trends in density on these grids.
2. Although trapping typically occurs during July-September, some inter-annual variation exists within that period, which may also influence trap results. To provide the best data for assessing population trends, grids should be trapped according to a standardized schedule during the annual trapping period, and the trapping period should be standardized among islands.
3. It is not known if other protocols such as the time of day when traps are opened, checked, and closed, types of bait, and types of traps have been kept constant across years. These should be standardized to the extent feasible.
4. Sampling is not distributed across the island to represent all habitat types and geographic areas, so it is unknown whether trend data represent the entire island. This is a challenge on all the islands because all islands have areas that are too steep, rugged, or inaccessible to trap. We therefore suggest that (a) an attempt is made to distribute trapping across the island as much as possible, and (b) that habitat use and selection studies be conducted to determine if under- or over-representation of certain habitat types or geographic parts of the island introduces bias into analysis of trends (see Section 4.5.3).

Survival, mortality, and reproduction

Survival rates can be estimated from annual capture data on marked animals, and capture histories of individually-identified foxes have been used to estimate apparent survival on San Miguel Island, using trap data and the Cormack-Jolly-Seber model in program MARK (Roemer et al. 2001b, Coonan et al. 2005). However, it is not possible to obtain information on causes of mortality from annual trap data. In addition, trap data, usually generated on an annual basis and providing inferences on the annual trapping period beginning 2 years prior, would not allow immediate management response if a disease outbreak occurred or if eagle predation suddenly increased. Furthermore, survival estimates generated from trapping produce only an estimate of apparent survival, which does not account for emigration and therefore underestimates true survival. For these reasons, data collected on trapping grids on San Miguel Island are unable to provide necessary data on survival or cause-specific mortality rates.

However, starting in 1998, 15 foxes were monitored daily for about 12 months, until they were removed for captive breeding, to document survival and cause-specific mortality rates (Coonan et al. 2005). Since 2004, when animals were first released back into the wild, all released and many wild-caught animals are radiocollared and tracked for survival. As of June 2006, about 40 radiocollared animals were being monitored for survival (i.e., checked for a live signal) twice weekly (T. Coonan, NPS, pers. comm.). The Fox Health TEG recommends that signals of at least 40 animals should ideally be checked daily, but at a minimum of every 2-3 days in the winter and every 1-2 days in the summer (Section 2.4.2). These guidelines are based on the probability that a carcass can be located and transported to UC Davis rapidly enough for a meaningful necropsy to be feasible. Therefore, current survival monitoring on San Miguel Island is approaching the recommended protocols (if at least 40 radiocollared animals are maintained); however, the frequency of signal checks would need to be increased, especially in the summer months. We suggest that future analyses of data on radiocollared animals use the known fate model in MARK to perform survival estimates, rather than the simple Kaplan-Meier estimator.

For data on reproduction, grid data may be used to generate an estimate of the proportion of females lactating, if trapping is conducted late June or early July every year. The ratio of yearlings to adults captured during annual trapping can provide a useful index of recruitment, and these data can be obtained via annual grid trapping (corrections for age-specific recapture rates should be made if such differences are detected). Ideally, the timing of trapping should be standardized across islands so that valid comparisons can be made across islands.

4.4 Monitoring Protocols on San Miguel Island

4.4.1 Feasibility Considerations for Monitoring

Section 2.2.2 outlines general constraints and considerations related to field protocols that pertain to all islands. In addition to those general constraints of access, timing, weather, animal welfare, and cost, monitoring on San Miguel Island must consider the following specific issues:

1. Although San Miguel Island has relatively gentle terrain, and most vegetation is low and easy to traverse, there are several areas, primarily along the southern coastline, that are inaccessible due to steep and unstable slopes and cliffs (Maps 4-3 and 4-4).
2. NPS desires to limit foot traffic on the island to protect sensitive plant species. For example, the general public must stay on trails and may only venture beyond the ranger station if accompanied by a ranger. Therefore, monitoring protocols that would limit excessive cross-country traffic are favored. The existing network of trails is limited, especially at the west end of the island.
3. The number of biologists working on San Miguel Island is usually limited to one to three people, due to fiscal constraints on hiring personnel and limited housing on the island. This limits personnel availability for field work, especially when other duties (such as care of the captive population and interactions with the visiting public) exist. It is likely that additional field personnel would be necessary for the short annual trapping period.

4.4.2 Candidate Trapping Protocols

As described in Section 2.4.1, we had three options for trapping protocols on San Miguel Island: island-wide random trapping, traditional trapping of large grids, and multiple small trapping units (Box 2-2).

We first evaluated the feasibility of mark-recapture sampling using island-wide random sampling (Box 2-2), due to the statistical robustness of this method. Using two density levels (1 fox/km^2 and 4 foxes/km^2), and a plausible range of fox movement patterns and capture probabilities, we simulated the number of traps and trap-nights required to obtain sufficient recaptures to generate a population estimate with the desired precision. Two variations were examined: one in which trap locations were placed in random locations each night and one in which traps were systematically placed with even spacing across the entire island and the entire grid was shifted in a random direction by one-half the inter-trap distance each night (Appendix K, Addendum A). In general, the second variation provided higher precision for a given number of traps and trap-nights. However, to obtain a population estimate, $\hat{N}$, with a coefficient of variation of ≤20%, the results suggested that 39 traps set at 1,000-meter spacing would have to be moved to new locations for at least 12 nights. This was deemed infeasible by San Miguel Island staff, primarily due to the large number of traps that would need to be moved each night by a small group of field biologists. This method was abandoned due primarily to limitations in staff.

We also evaluated precision resulting from existing protocols (existing grids and number of trap-nights) and variations of these protocols involving different numbers and sizes of grids and different trapping durations. Given a particular trap layout and duration, the resulting precision depends largely on the number of recaptures. Recaptures, in turn, are determined by the density of foxes and their behaviors which influence detection by the sampling system. Program DENSITY models these behaviors using two detection parameters to describe movement patterns and capture probabilities when encountering traps (Efford 2004, Efford et al. 2004, Appendix K). Simulations were run with density set at 2 foxes/km^2, similar to the current estimated density of 2.2 foxes/km^2, and a range of theoretical, yet plausible detection parameters. In addition, V. Bakker generated a best estimate of detection parameters, using actual trap data from multiple years and multiple islands, and the program DENSITY. Data archives from the many years of field work on the various islands provided a valuable resource for identifying these best estimates. Simulations were therefore conducted with detection parameters set at a plausible range of values as well as a best estimate to examine and compare resulting precision with differing levels of effort (Sections 2.4.1, Appendix K).

Simulation results suggest that 33 recaptures would be necessary to obtain a mean CV($\hat{D}$) of 20%, and 40 recaptures is recommended as a design target to ensure that the desired CV is consistently attained (Appendix M). Based on simulations, Figure M-7 in Appendix M indicates the precision expected at varying densities when different numbers of units are trapped, with CV($\hat{D}$) = 20% representing approximately 33 recaptures, while Figure M-4 shows the number of units required to obtain 40 recaptures at varying densities. The latter therefore provides a more conservative goal, which would assure a CV($\hat{D}$) of ≤20%. Our goal was to identify scenarios that would approach 40 recaptures but we also considered less intensive efforts considered more economical and logistically feasible. We estimated expected precision with the equation CV($\hat{D}$) = $0.894m^{-0.297}-0.116$, where m = the number of recaptures (Appendix M).

Existing (2006) grids were found to generate density estimates with relatively low precision, CV ($\hat{D}$) = 38-64%, depending on detection parameters simulated, compared to the target precision of CV($\hat{D}$) ≤ 20% (Table K-3, Appendix K). A variety of grid configurations with the same total number of trap-nights was simulated, but a substantial improvement in precision was not observed. We therefore increased the total number of trap-nights (with several variations in grid configuration) to determine when the target precision was obtained. This varied slightly by choice of detection parameters. Adequate precision can be obtained when trapping is extended to five grids of at least 30 traps each, with inter-trap distance of 200 meters, and trapping is conducted for six nights (Appendix K). Relatively good precision (CV($\hat{D}$) = 18-32% depending on detection parameters) is obtained when five grids with dimensions of 6x6 traps are trapped for 6 nights, and slightly lower precision (CV($\hat{D}$) = 20-35% depending on detection parameters) is obtained if these grids are reduced to a dimension of 5x6 traps. These two scenarios are presented as San Miguel Island Trapping Scenarios A and B. We produced a suggested map of these two scenarios by placing (and orienting) the grids randomly on San Miguel Island, with the following rules implemented: (a) grids must be ≥1,500 meters apart to minimize the chance of an individual fox moving between grids, (b) traps should be ≥100 meters from the shoreline to avoid disturbance to sea birds and marine mammals, and (c) trap locations should avoid steep slopes, with ≥30% (16.7°) slope, when possible to reduce risks to field personnel (Scenarios A and B shown in Maps 4-5 and 4-6, respectively). Although grids could be placed closer together, maintaining at least 1,500 meters between grids eliminates the need to account for inter-grid movements, which would be necessary given that the grids are not trapped simultaneously.

We also explored the use of transects, which could be more practical for small field crews to conduct. Simulation results indicated that parallel paired lines (referred to here as *units*) produced better results than single straight lines with the same number of traps and spacing (Appendix M). We evaluated the number of units, with dimensions of 2x6 traps spaced at 200 meters and trapped for 6 nights, that would be needed to obtain adequate precision (Appendices K and M). This evaluation was conducted in the same manner as evaluation of the larger grids;

however, a range of densities was also evaluated. Simulation results suggested that at the current density of 2.2 foxes/km^2, at least 16 such units would be required to consistently obtain the targeted precision. We randomly placed units on a map, following the same set of rules as for Scenarios A and B, and found that, due to the limited size of the island, a maximum of seven units could be placed on the island if they were to be kept 1,500 meters apart to minimize the chance of animals moving between units. As with the spacing of grids, maintaining at least 1,500 meters between units eliminates the need to account for inter-unit movements, and the nearly "regular" spacing of units that results from this spacing rule approaches a systematic sample which should have reduced sampling variance. At a density of 2.2 foxes/km^2, the use of seven 2x6 trap units is expected to generate a density estimate with precision of roughly 28-35%, depending on detection parameters. The desired precision target would be obtained with this scenario if density were to increase to approximately 4.5-5 foxes/km^2 (Appendix M). We present this scenario as San Miguel Trapping Scenario C (Map 4-7).

The three San Miguel Island scenarios (A, B, and C) all produce a more precise estimate of density than current trapping grids do. However, there is no correct answer on choice of grids, as there are trade-offs in each case. Scenario A produces the best precision but, at a total of 1,080 trap-nights, it is labor-intensive. Scenario B, with a total of 900 trap-nights, may be more feasible, but with a slight reduction in precision. Scenario C, with a total of 504 trap-nights, is more logistically feasible but at a further loss of precision. However, representation of the island may be highest with Scenario C, due to wider dispersal of trap effort across the island, and adequate precision could be obtained if fox densities increase to 5 foxes/km^2. In addition to improved precision, all three scenarios are also considered superior to the current (2006) trapping grids because the location of grids/units was randomized, and the imposed distance of 1,500 meters between grids/units. When inter-unit movements are minimal, data can be pooled to increase precision of detection parameters and thus overall estimates. We therefore suggest that one of the three scenarios be chosen over the existing trap grids. The expected precision of any of these three scenarios could likely be increased by increasing the number of nights trapped; however, this may be detrimental to foxes that are caught repeatedly. Trap-happy behavior may create a challenge with any trapping regime for this species and could bias estimates to an unknown degree and possibly reduce precision slightly. Use of maximum likelihood methods, currently being incorporated into program DENSITY, will make it possible to include a learned response in the model; however, further analyses would be necessary to properly model this behavior in island foxes (M. Efford, pers. comm.).

4.4.3 Representation Analysis of Selected Candidate Trapping Protocols

To determine how well selected candidate trapping protocols represent habitat variability on the island, we conducted representation analyses using both univariate and multivariate techniques and compared two of the candidate protocols (Scenarios B and C) to habitat variability in island-wide areas and those sampled by existing protocols (Appendices A and F). In our comparison to existing protocols, we included an analysis of grids trapped during 1993-1998 because this was the established protocol until the remaining foxes were removed from the wild (due to threat of golden eagle predation), and the 2006 protocol was only recently established and designed primarily due to limited personnel availability. We did not include Scenario A in our analyses because it was assumed that it would provide similar or slightly improved representation compared to Scenario B, as it is similar to Scenario B except for using slightly larger grids.

Univariate analyses (Appendix A) indicate that all four trapping scenarios included in this analysis (two existing and two new) sampled areas with lower slope and ruggedness than island-wide areas. This pattern will likely be observed in any feasible trapping protocol on San Miguel Island, as steep and rugged cliffs and bluffs near the shore can not safely be sampled. The absolute differences in slope and ruggedness between sampled and island-wide areas are small in all cases, however, and, as discussed in Appendix A, these small differences may not have biological significance. Areas close to the shore are under-sampled with all protocols, which is also unavoidable with any feasible protocol, for the same safety reasons. Areas sampled with Scenario C resembled the island the most closely in distance to the shore and in ruggedness (two measures that are correlated). All scenarios sampled areas closer to trails, most likely due to the fact that trails occur closer to the middle of the island than to the shore. The 2006 protocol was most extreme in its bias toward areas near trails, as traps were purposely set along and near trails. This may bias trap results if foxes tend to move along trails or select areas near trails. Three of the protocols (1990s protocol, 2006 protocol, and Scenario C) also differed from island-wide areas in distance to developed areas. The significance of trapped areas being closer to developed areas is unknown but may be low, given the small physical footprint of developed areas on San Miguel Island. The same three protocols also trapped areas closer to freshwater. Because a map of freshwater sources was lacking for this island, we used the USGS hydrology layer as a surrogate. This layer represents drainages and ravines, which, in themselves may have relevance for foxes, in that they may provide valuable resources such as denning sites or foraging areas.

Although Scenario C resembled the island most closely in terms of ruggedness and distance to shore, Scenario B sampled the island most adequately in terms of distance to developed areas and to freshwater, and it also differed the least from the island in representation of the five vegetation categories included in this analysis. It is likely that Scenario A, which we did not evaluate as it is similar to Scenario B except for using slightly larger grids, would sample the island more effectively than Scenario B.

Multivariate analyses (Appendix F) indicated that both the large grids of the 1990s and the current (2006) small grids under-represent all multivariate habitat types, under-sampling steep rugged remote shoreline and areas remote from development regardless of proximity to drainages and trails. Proposed trapping scenarios better represent the island. Scenario B under-samples steep rugged remote shoreline and over-samples remote interior trails but is otherwise unbiased. Scenario C adequately represents most multivariate habitat types including steep rugged remote shoreline, but under-samples terrain far from drainages and development. Overall, Scenario C provides the most representative sampling of multivariate habitat types. Biases in multivariate habitat sampled by proposed scenarios likely result from logistical constraints placed on trap unit location to ensure feasibility of the trapping effort. Regardless of scenario chosen, density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to assure that habitat biases do not bias monitoring program results.

We suggest that future studies on habitat use and selection would provide valuable information on whether the above differences may bias trapping data. In the absence of further knowledge on fox habitat use and selection, it is not known which of the above measures has the most relevance to trapping protocols; however, our analyses suggest that any of the proposed scenarios will sample the island more adequately than the 1990 or 2006 protocols.

4.4.4 Survival and Cause-Specific Mortality Monitoring

San Miguel Island's small size and relatively gentle terrain should make frequent monitoring of radio signals feasible. However, limitation in personnel will pose a challenge on this island, as there are often only one to two biologists on the island, and other duties may interfere with their ability to check all signals on a daily basis. In addition, because there are no roads, time is required to walk to points where signals can be heard.

Signals from most of the island may be picked up from two primary vantage points: San Miguel Peak and Green Mountain. A hike from the main housing facility (Ranger Station) to Green Mountain via the top of San Miguel is approximately 8 km (5 miles) round-trip, which should be feasible, assuming personnel are available. Signals may be difficult to pick up from foxes along the southern shoreline at the base of the steep escarpment, and may require additional effort. When personnel are present at the research station near Point Bennett, their assistance should be considered for monitoring on the west end of the island.

The use of remote telemetry receivers should be considered as a supplement to direct ground monitoring, and NPS staff (San Miguel Manager Ian Williams) has begun exploring this option (Section 2.4.2). Assuming a detection range (the distance over which a collar signal can be detected assuming a line-of-sight signal) of 5 km, several tall towers could likely detect signals across most of San Miguel Island. A viewshed analysis would be needed to determine the necessary number and most effective placement of such towers and to determine portions of the island that would not be monitored as part of the remote system (these areas would need to be monitored from the ground). Prior to the viewshed analysis, the detection range of collars should be confirmed in the field.

4.5 A Tiered Approach for Population Monitoring

4.5.1 Recommended Long-Term Trapping Protocols

We recommend that trapping be conducted according to one of the following three scenarios, based on an evaluation of trade-offs such as expected precision, logistical feasibility, and representation of habitat variability on the island:

- Scenario A: 5 grids with 6x6 traps, trapped for 6 nights, for a total of 1,080 trap-nights annually (Map 4-5)
- Scenario B: 5 grids with 6x5 traps, trapped for 6 nights, for a total of 900 trap-nights annually (Map 4-6)
- Scenario C: 7 units with 2x6 traps, trapped for 6 nights, for a total of 504 trap-nights annually (Map 4-7).

Trapping should ideally be conducted at the same time each year, and be synchronized with timing on other islands, to facilitate the most accurate comparisons across years and islands. We suggest that July represents the most optimum trap period (Section 2.2.2). Furthermore, to reduce the probability of fox moves between sampling units, all units should be trapped in as short a time period as possible.

4.5.2 Recommended Monitoring for Survival and Cause-Specific Mortality

We recommend the following actions to track survival and cause-specific mortality for San Miguel Island foxes:

1. Annually radio-collar at least 40 foxes with mortality-sensing VHF collars, according to the guidelines in Section 2.4.2. We note that foxes on the very open terrain of San Miguel Island are likely especially susceptible to predation by golden eagles that may visit from a neighboring island, so chance visitation of this very small island by even a lone eagle could have population viability implications. Because golden eagles have been difficult to detect, even when eagle predation is known to occur, these collars should be widely distributed across the island and monitored frequently. We expect that most, if not all, of the 40 foxes may be captured and radiocollared during trapping designed for collection of demographic data, while a small amount of targeted follow-up trapping may be necessary if inadequate numbers animals are captured or if previously collared animals need to be captured to remove old collars. Some level of collar failure and/or mortality is expected to occur every year; therefore, the initial number of animals collared should ideally be increased to at least 45. Additional follow-up trapping may be necessary if the number of radiocollared animals falls below 40.
2. Dedicate sufficient personnel hours to ensure that signals of all radiocollared foxes can be monitored from the ground at least every 2 days during the summer and every 3 days during the winter, with a preferred schedule of a signal check on every animal each day.
3. Explore the option of monitoring foxes via GPS collars or via aerial telemetry as discussed in Section 2.4.2. The latter may be cost-efficient if aerial monitoring will be used on Santa Cruz and Santa Rosa islands, and if the additional effort to check San Miguel Island foxes during the same flight is feasible and cost-efficient.
4. Continue exploring the option of a remote monitoring system to augment or replace monitoring efforts on the ground.
    - Conduct pilot studies to determine actual, in-field, detection ranges for telemetry signals as a function of terrain, location, tower heights, etc.
    - Conduct a viewshed analysis to determine number and locations of towers. This would also help determine zones (e.g., the bottom of some canyons) from which a collar signal will not be detected by a tower).
5. If the above investigations warrant the use of remote telemetry on towers, construct towers and install and test the automatic recording system.
6. Have personnel on call on the island to immediately locate and investigate mortalities, and develop a standard protocol for transporting carcasses to UC Davis for necropsy.

4.5.3 Recommended Research Modules

Monitoring protocols outlined in this report will produce a standardized long-term flow of demographic data on island foxes. In addition to providing information for management and conservation decisions, this dataset will provide a context for additional research studies on island fox biology, environmental factors affecting the viability and dynamics of fox populations, and management intervention. Information gained from research projects may, in turn, be used to refine future monitoring protocols or analyses of monitoring data. Monitoring and research modules are therefore complementary, although research modules may only occur for short time periods while monitoring is designed to be an ongoing effort.

Recommended research modules for San Miguel Island include:

1. Vegetation mapping and monitoring. The island-wide vegetation map should be updated every 5-10 years. As part of this effort, field work should measure vegetation height, structure, and composition at pre-determined sites to track changes due to habitat recovery, climate change, and human activity. Such data are useful for understanding temporal and spatial patterns of habitat use and risk of golden eagle predation.
2. Habitat and space use**.** Habitat selection and space use studies should be conducted to address specific behavioral and demographic patterns relative to the trail system, the shoreline, or areas of human activity, as well as to determine home range size, movement patterns, and dispersal related to density. These data will be useful in interpreting annual trap data (e.g., to determine if over- or under-representation of certain habitats are likely to bias population estimates up or down). The presence of radiocollared animals (for survival monitoring) will greatly facilitate such studies.
3. Community dynamics. The relationships between island foxes and other species should be useful in understanding predator-prey relationships and potential competition.
4. Disease and health**.** Although standardized disease and health monitoring will be conducted every year, as specified by Fox Health TEG guidelines, some tests or the intensity of testing may vary from year to year, as determined by veterinarians and epidemiologists, and some focused short-term research projects may be warranted.
5. Reproduction and early pup survival. Although annual trap data will provide some information on reproduction (e.g., indexed by the proportion of captured females exhibiting signs of reproduction, or by the ratio of yearlings to females), further research is needed to better estimate reproduction, pup survival, and factors influencing these measures. The presence of radiocollared foxes will facilitate such research, but other methods such as use of remote cameras or genetic techniques (such as via scat or hair sampling) may be necessary.
6. Effectiveness of remote telemetry stations. The option of a remote monitoring system to augment or replace survival monitoring efforts on the ground should be further explored. This should include pilot studies to determine actual, in field, detection ranges for telemetry signals as a function of terrain, location, tower heights, etc., and a viewshed analysis to determine number and locations of towers needed to monitor the island adequately (Section 2.4.2).

7. Effectiveness of camera stations. It is unclear at this time to what degree remote camera stations may be useful for supplementing or replacing other monitoring components. A pilot study to determine whether mark-recapture sampling using remote cameras is a feasible method of monitoring trends or estimating population size should be considered. The use of cameras as a means of collecting quantitative information on specific reproduction measures (e.g., litter size, pup survival) should further be explored.

8. Indices of trend. We recommend further research on the use of sign (e.g., scat, tracks, camera "observations") as an index of population trend. This should include statistical comparison to more formal estimates of population trend.

9. Trap protocols and analysis of trap data. In our analysis of potential trap protocols, trap detection parameters were refined with the use of existing data from multiple islands; however, increased understanding of the behavior of foxes in relation to trapping could improve the choice of trapping protocols and the analysis of trap data. For example, it may be possible to more adequately model trap-happy behavior and incorporate this into density estimation models.

   Similarly, fox movement behaviors may influence the appropriate methods of data analysis. For example, further research should be conducted to evaluate whether home range shape (e.g., elongated home ranges due to movement along roads, trails, and ridges) influences or biases density estimates, and how trap protocols and analyses may account for such potential influences.

   Further research is also needed to evaluate a potential approach for estimating density by combining telemetry and trapping data (Section 2.3.2). Generally, this approach calls for delineating the area associated with a trapping unit, determining the proportion of locations within the trapping area for radio-collared animals, and estimating density for each unit based on the relationship between the proportion of locations within the trapping unit and probability of capture. This method requires further development for optimal design to assess how precision would vary with different grid sizes, trapping durations, numbers of radiocollared foxes, telemetry location frequencies, and telemetry location precision.

Section 3.2 outlines other biotic and abiotic data that should be routinely monitored and integrated with fox data.

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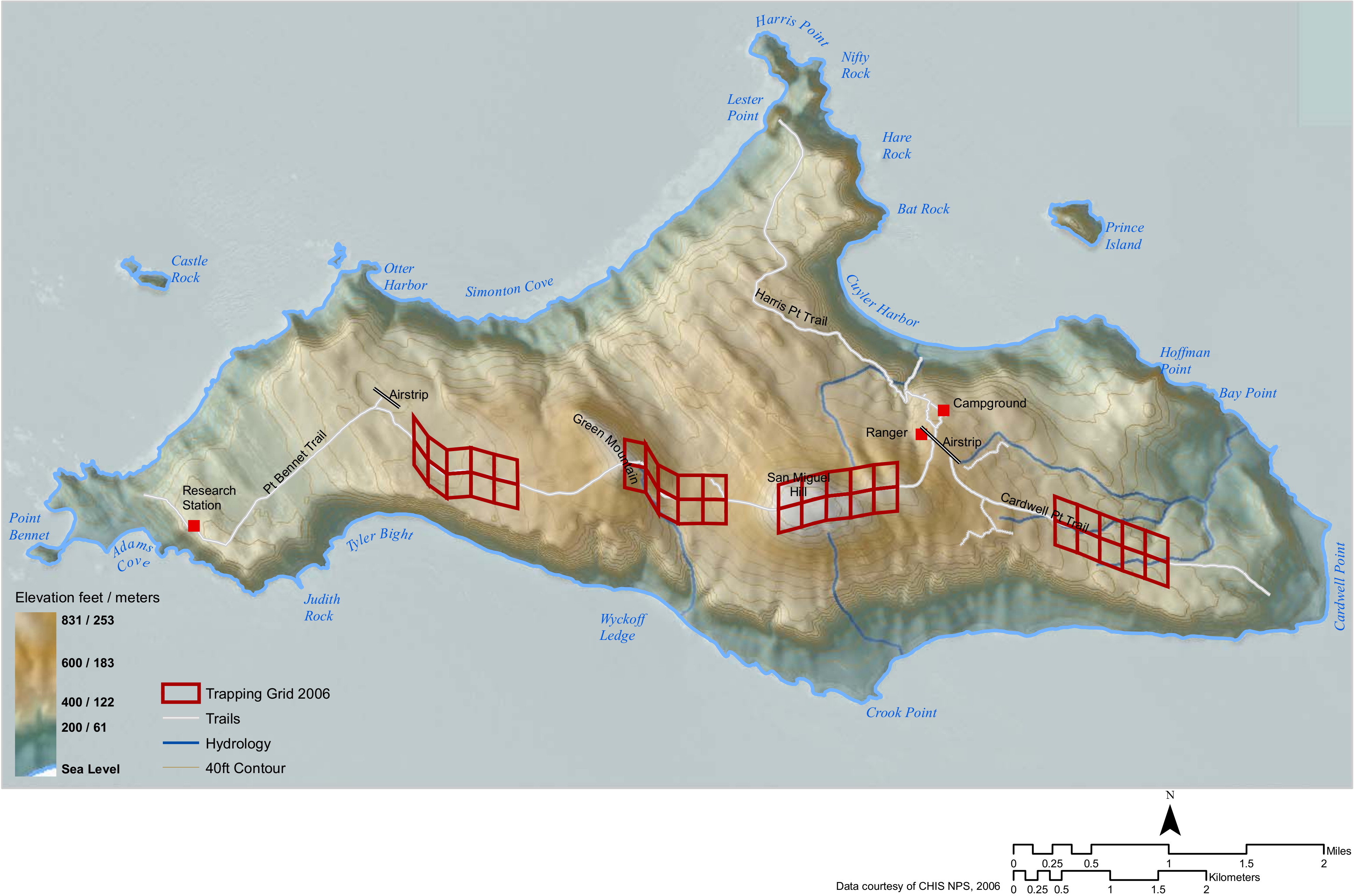
San Miguel Island

Map 4-1: Existing Trapping Grids



Data courtesy of CHIS NPS, 2006

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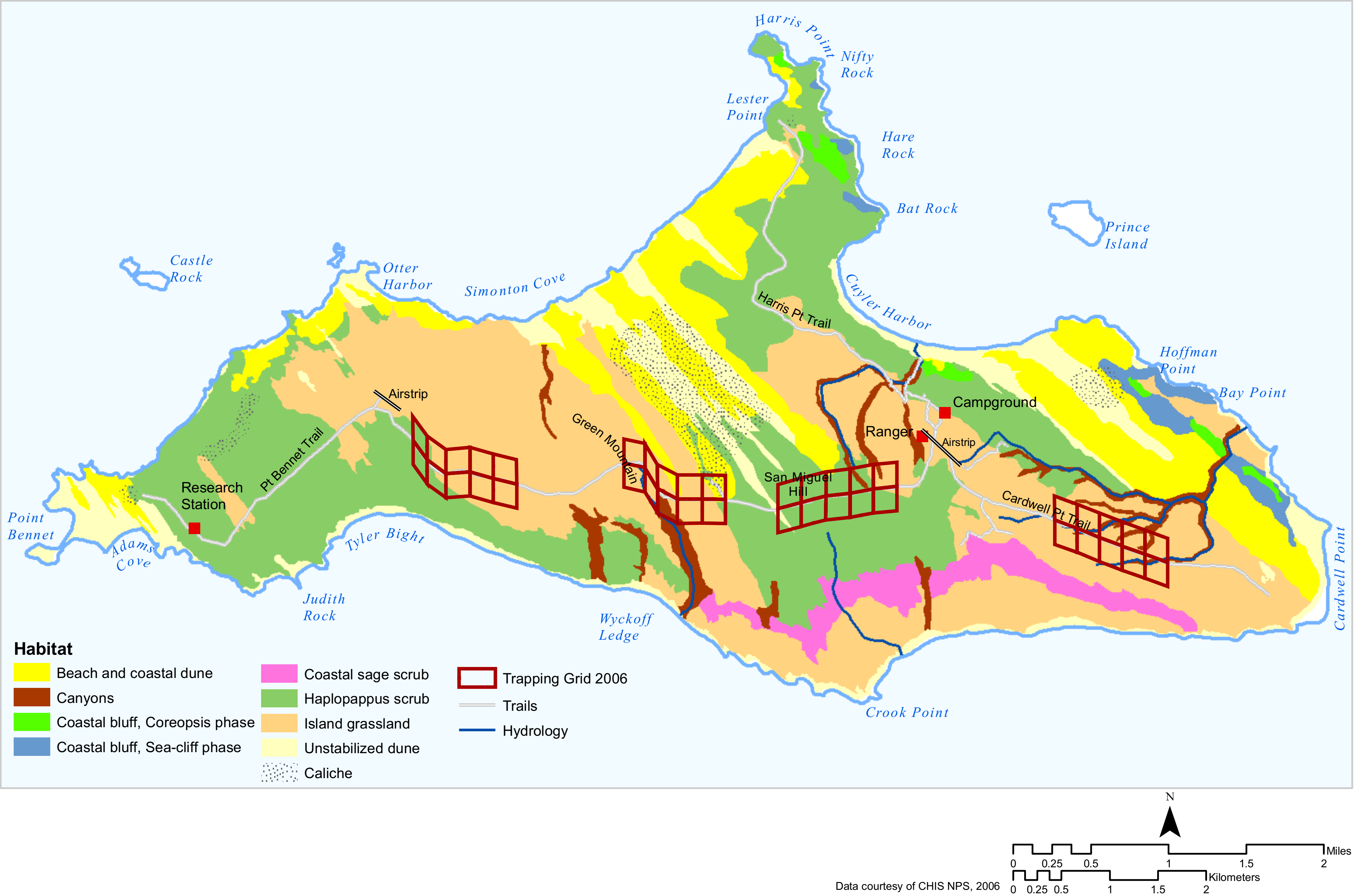
Map 4-2: Existing Trapping Grids in Relation to Vegetation



Data courtesy of CHIS NPS, 2006

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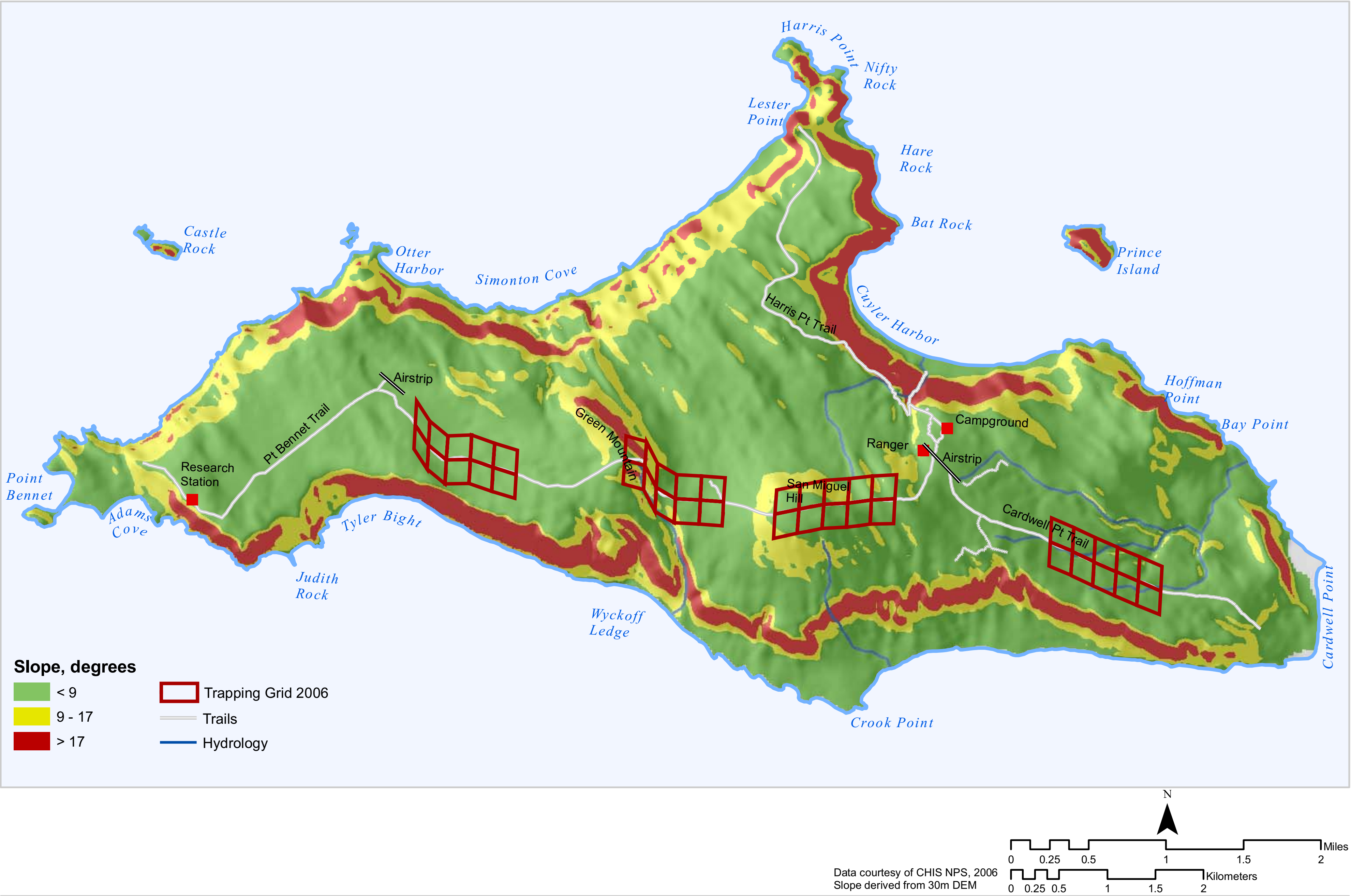
Map 4-3: Existing Trapping Grids in Relation to Slope



Data courtesy of CHIS NPS, 2006
Slope derived from 30m DEM

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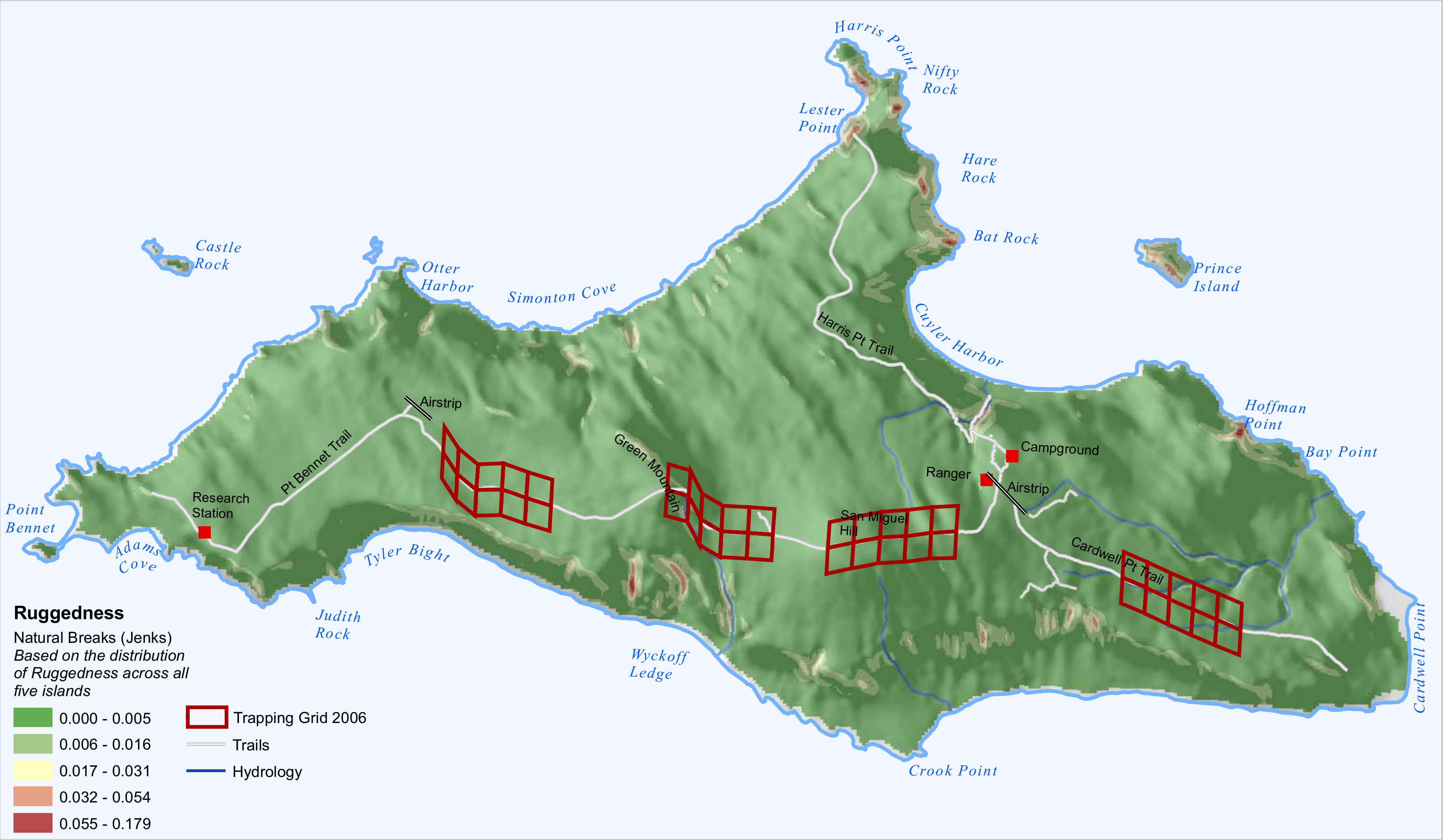
Map 4-4: Existing Trapping Grids in Relation to Ruggedness



Avenue script created and provided by
M. Sappington [National Park Service]
and K. Longshore [U.S. Geological Survey]

Data courtesy of CHIS NPS, 2006
Slope derived from 30m DEM

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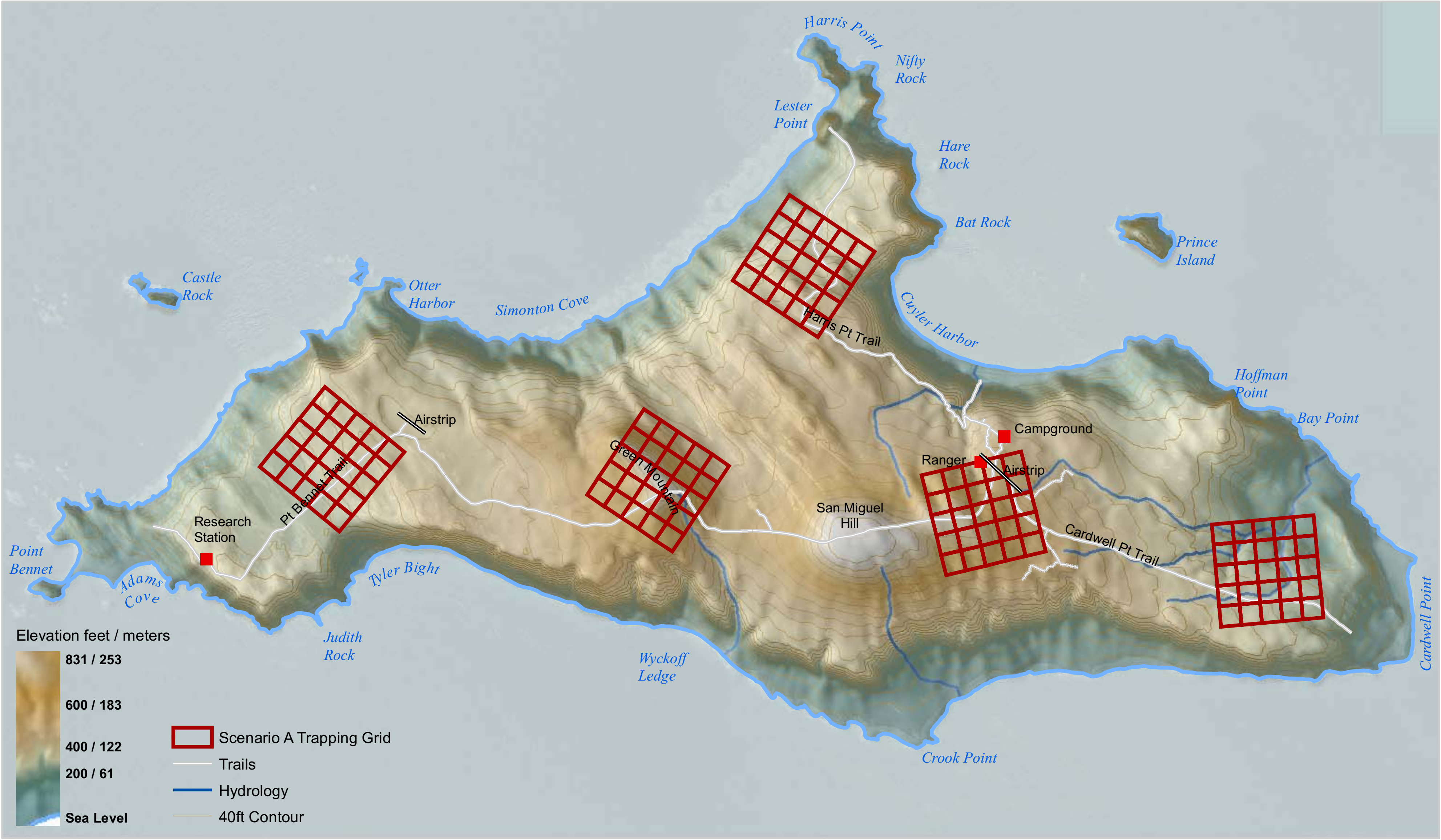
Map 4-5: Trapping Scenario A



Data courtesy of CHIS NPS, 2006

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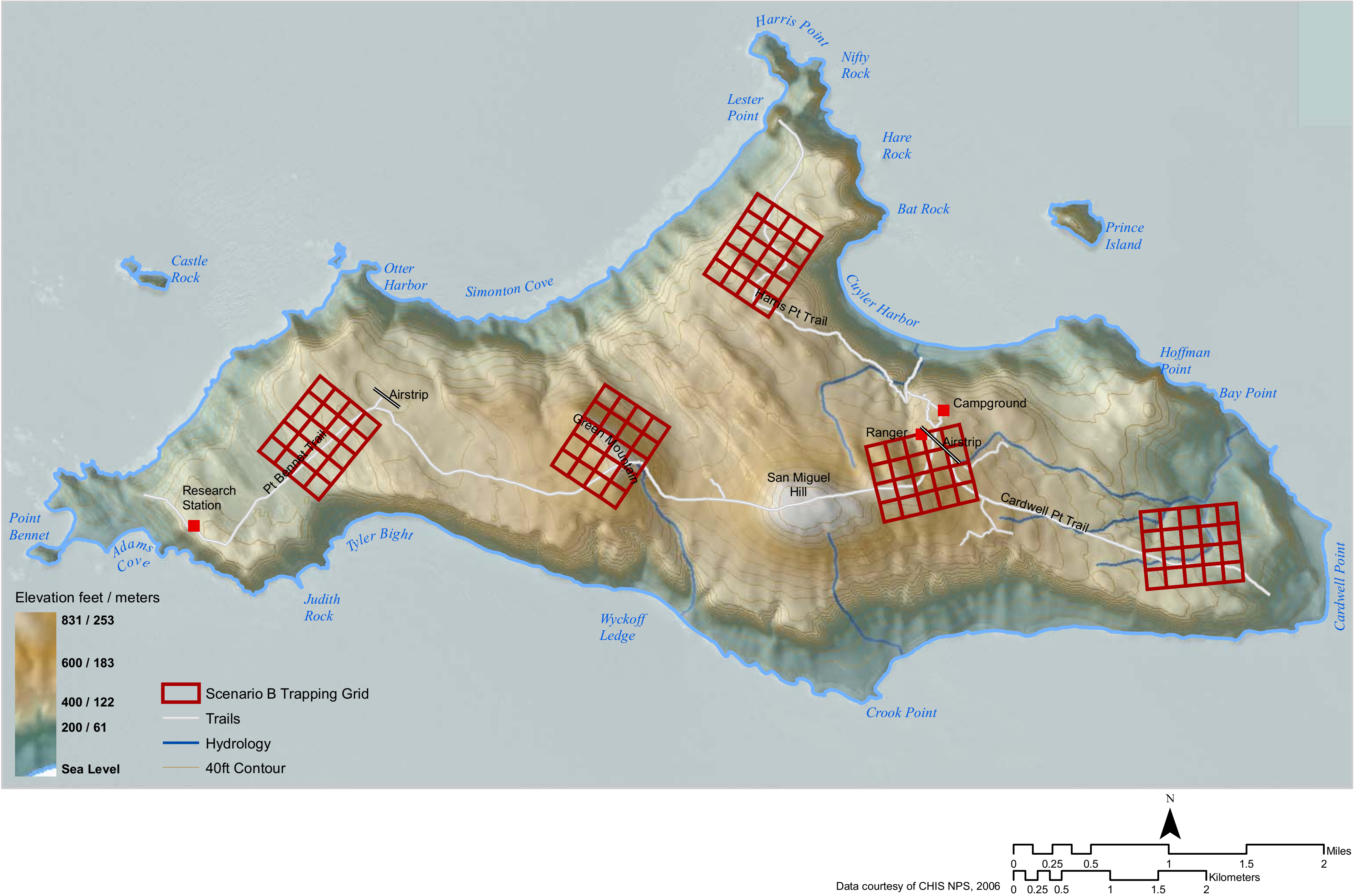
Map 4-6: Trapping Scenario B



Data courtesy of CHIS NPS, 2006

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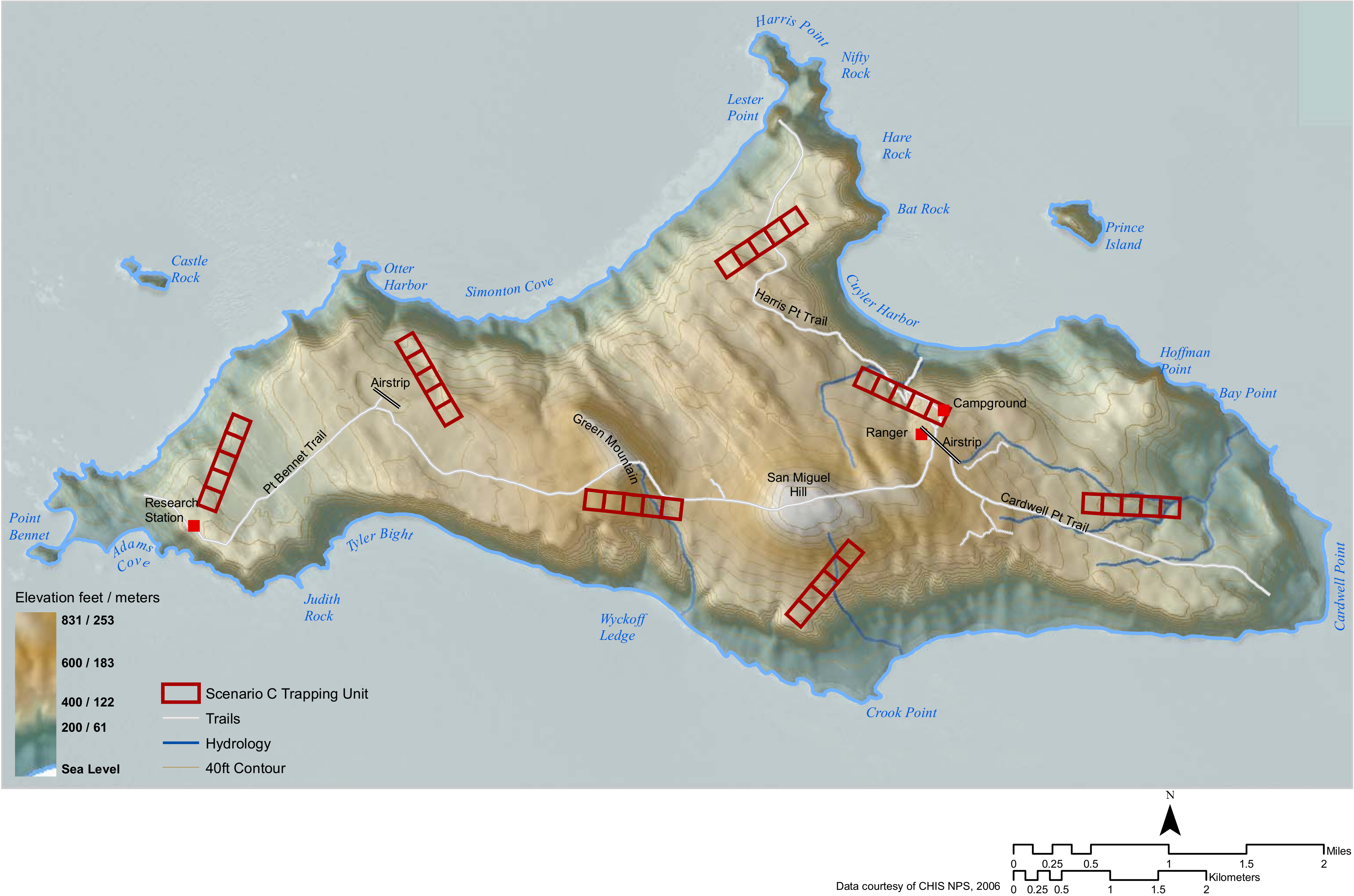
Map 4-7: Trapping Scenario C



Data courtesy of CHIS NPS, 2006