Executive Summary

Island foxes (*Urocyon littoralis*) inhabit the six largest Channel Islands off the coast of southern California, with a separate subspecies recognized on each island: San Miguel Island fox (*U. l. littoralis*), San Nicolas Island fox (*U. l. dickeyi*), San Clemente Island fox (*U. l. clementae*), Santa Catalina Island fox (*U. l. catalinae*), Santa Rosa Island fox (*U. l. santarosae*), and Santa Cruz Island fox (*U. l. santacruzae*). Due to their limited geographic distribution and small population sizes, foxes on all six islands have been listed as Threatened by the State of California, and all subspecies except those on San Nicolas and San Clemente have been listed as Endangered by the U.S. Fish and Wildlife Service (USFWS) due to recent precipitous population declines and high risk of extinction.

Due to the persistent high risk of this island species, robust monitoring of fox populations and their threats is a key component of recovery and long-term management. This document presents a framework for population monitoring for five subspecies of island fox on San Miguel, San Nicolas, Santa Catalina, Santa Rosa, and Santa Cruz Islands. A monitoring framework previously developed for the U.S. Navy on San Clemente Island, in addition to years of monitoring and research on all six islands, provided the foundation for the current effort. This document thus represents the first comprehensive synthesis of monitoring data, objectives, and protocols across multiple Channel Islands with foxes.

Sections 1-3 of this report describe the considerations and approaches used to identify specific monitoring objectives, determine parameters to address these objectives, and develop protocols to measure these parameters. Sections 4-8 present illustrative island-specific examples of monitoring scenarios designed to address current monitoring objectives, but with different levels of effort and precision. We provide at least two alternative trapping scenarios for each island, along with expected precision (e.g., for resulting population estimates), effort required, and estimated habitat representation. It is expected that island managers will tailor and adapt protocols for on-the-ground use, based on their resources and priorities, understanding that there is generally a trade-off between monitoring intensity and information value.

Monitoring Objectives and Parameters

This framework reflects the culmination of years of investigation, discussion, and planning by the Island Fox Integrated Recovery Team, island managers, veterinarians, population modelers, statisticians, and other scientists who have contributed to the understanding of this charismatic species. The motivation for this effort was the recognition that monitoring objectives and protocols have varied among islands and over time. Going forward, the monitoring objectives for this framework address the essential core of information in which managers should invest, recognizing logistical and monetary constraints and the inherent trade-offs for precision. These objectives are:

1. Track recovery of fox populations relative to recovery criteria, which will be defined in the Recovery Plan for this species developed by the USFWS.
2. Determine when delisting is warranted (as defined in the USFWS Recovery Plan).

3. Guide island-specific management decisions such as those related to captive breeding, vaccination, eagle removal, and management of human activities.
4. Refine parameter estimates for population viability analyses (PVA), and facilitate other cross-island comparisons.

This framework incorporates the general philosophy of the Recovery Coordination Group (RCG), which emphasizes close tracking of fox mortality rates to identify the presence and intensity of the fox's primary threats, namely eagle predation and disease, and to rapidly detect new threats. Precise temporal-scale knowledge of mortality is vital for triggering management actions to control these threats. Mortality rates, especially for adults, exert the greatest influence on the risk of extinction for island foxes in population viability analyses, and observed mortality rates can be used to accurately predict future risk. Population size estimates and general trends in abundance can help corroborate conclusions regarding population status made from mortality data. While other philosophical approaches emphasize precise estimates of population size and abundance trends, our reliance on mortality rates derives from the commitment to monitor mortality precisely and the relationship between mortality rates and population status.

Tracking Recovery

Based on this general philosophy, management goals of island managers, and further input from population modelers and Technical Expertise Groups (TEG), the following monitoring parameters were targeted for the purpose of tracking and determining recovery:

- Annual mortality rates at high precision (with associated cause-specific mortality rates)—sufficient to detect an annual eagle-specific mortality rate of ≥2.5%, averaged over 3 years.
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- Annual population size, with 80% confidence interval.

In anticipation of a recovery plan for the island fox, the RCG, land managers, and population modelers proposed recovery criteria, with the following related to monitoring:

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annual island fox mortality rate caused by golden eagle predation of ≥2.5%, averaged over 3 years.

These components of the proposed recovery criteria, together with the RCG philosophy, influenced the targeted precision of monitoring protocols in this framework, i.e., high precision in mortality rates but greater flexibility in precision of population and trend estimates. This framework provides protocols that estimate true population size (N), with an estimate indicated by a “hat” ($\hat{N}$).

Guiding Management

Island managers identified the following additional parameters needed to guide management decisions:

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- Habitat-specific survival (Santa Cruz).
- Reproduction measured in terms of annual recruitment (San Miguel, Santa Rosa).
- Disease and health profiles, as sampled from all dead foxes and from a subset of the living population, based on sampling protocols determined by the Fox Health TEG (all islands).

Population Sampling Considerations

Experts involved in developing a previous island fox monitoring framework for the U.S. Navy on San Clemente Island recommended trapping and radio telemetry as key components for islandwide fox monitoring to address mortality rates and causes. Trapping also provides the best means of estimating population sizes with known precision and confidence intervals. The use of GPS collars provides an additional means of monitoring habitat use and, possibly, mortality. To minimize stress to foxes, as well as labor and equipment costs, we recommend scenarios in which both these objectives may, for the most part, be met with one annual trapping effort, thereby making the best use of personnel resources and reducing disruption to foxes that might occur from multiple trapping efforts.

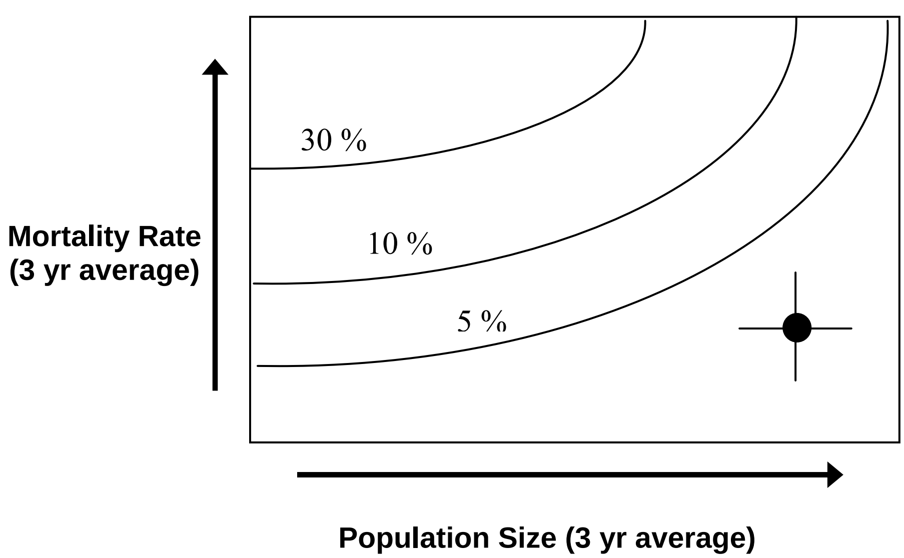
In determining specific trapping protocols, we considered a wide range of factors, including the ecology and behavior of the species, the logistical constraints on each island, and the selection of feasible monitoring methods that can provide the desired measurements in the most efficient and statistically robust manner. For island foxes, some key biological issues are their social structure (and existence of territories held by monogamous pairs), their ability to inhabit essentially every habitat type on the islands, and the timing of parturition. Access constraints on the islands, and concern for animal welfare, limit the choice and design of sampling protocols. Steep and rugged terrain, primitive road conditions or lack of roads, and large size of three of the islands make the use of large trapping grids infeasible, and ecologically sensitive areas seasonally restrict access to some areas for trapping.

The choice of trapping protocols involves tradeoffs between desired precision, feasibility and cost, and the extent of trapping; these, in turn, are influenced by the status of the population. For large populations with high survival, the risk of quasi-extinction is low; that is, these populations lie far from the 5% quasi-extinction isocline (Box ES-1). High precision in population estimates may be less important in such cases, compared to populations with smaller N and/or higher mortality, and managers may choose to reduce the extent of trapping and subsequently generate population estimates with lower precision (i.e., with CV >20%), thereby reducing costs, efforts, and potential risk and stress to foxes.

Our goal was to identify feasible trapping approaches for each island that would generate a statistically robust estimate with adequate precision and representation of island habitats. We provide recommended monitoring protocols that strive to estimate population size with a coefficient of variation (CV) of ≤20% when feasible. CV($\hat{N}$) is a measure of precision equal to the standard error of the estimate divided by the estimate itself. There is flexibility in the required precision of trend, and this level of precision will ultimately be decided by island managers, in their decision on trapping protocols. Although one standardized sampling approach across all islands would have been desirable, objectives and constraints differ somewhat across islands. Therefore, island-specific protocols must be tailored accordingly. The key parameters obtained from trapping should nevertheless be comparable among islands.

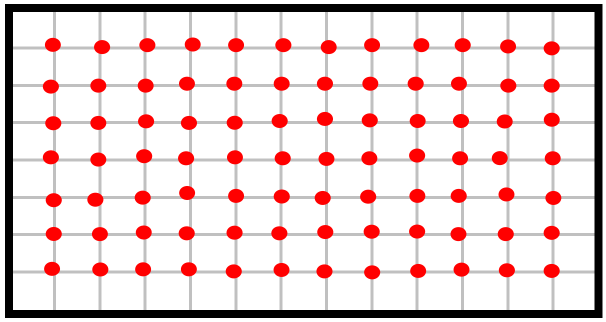
Box ES-1. Example of risk isoclines, with the status of a hypothetical population plotted.

The combination of a population's 3-year average size and mortality rate can be plotted to determine the population's status in relation to predetermined risk isoclines (shown here as 5, 10, and 30% risk isoclines). In this case, the population's status (shown as a point estimate along with 80% confidence intervals) is well below the isocline representing a 5% risk of quasi-extinction over 50 years, indicating a low level of risk.

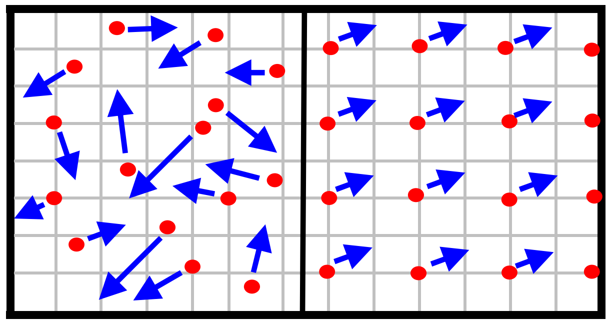


We considered five trapping approaches and configurations expected to provide robust parameter estimation for population size (and therefore also for trend):

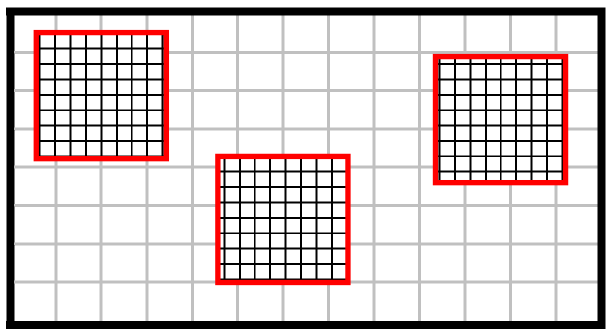
1. Island-wide systematic trapping. This was an option explored for San Clemente Island, in which traps are placed systematically and evenly on the island, <600 meters apart to allow for equal capture probability among all foxes. Population estimates are generated via mark-recapture methods with the entire island considered the effective trap area.



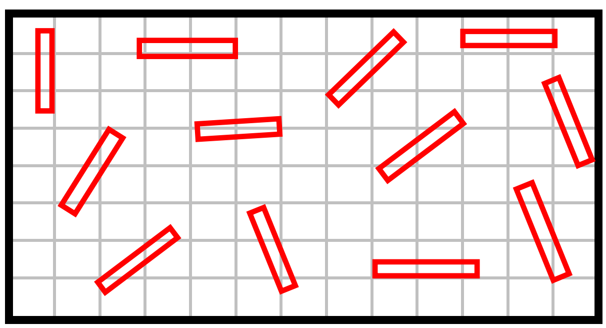
2. Island-wide random trapping. Traps are placed randomly or systematically on a grid (with ≤1200-meter spacing) and moved to new random locations individually or randomly as a shifted grid (up to ½ inter-trap distance), respectively, before each trapping occasion. Population estimates are generated via mark-recapture methods with the entire island considered the effective trap area.



3. Traditional trapping grids. Population size is extrapolated from local grid densities, based on (a) mark-recapture estimates of local abundance in combination with estimated local effective trap area (from distances moved by recaptured animals) or (b) spatially explicit capture-recapture methods, using movement and detection patterns alone.



4. Multiple small trapping "units." Population size is extrapolated from local units via spatially-explicit capture-recapture methods. Traditional mark-recapture methods cannot yield precise density estimates for transect-shaped units due to edge effects.



Island-wide systematic trapping is not feasible due to the large number of traps that would be necessary. We did not consider linear transect trapping, protocols currently used on Santa Catalina and Santa Cruz islands, because there is no statistically valid method for estimating the effective trap area around transects from trap data, thereby making it difficult to estimate density. We used simulation and analyses to examine and compare expected precision of other trapping configurations and protocols (e.g., number of traps, number of nights trapped). To account for spatial heterogeneity in local densities, we focused on protocols that use statistically rigorous sampling design, with trap layout determined by random, stratified, or systematic with random origin placement. For each island, we examined various trapping scenarios for expected precision, required field effort, and likely representation of habitat variability on the island, and compared them with required effort, statistical robustness, and representation of habitat variability of existing protocols.

Recognizing trade-offs between effort, feasibility, and the desire to maximize precision and habitat representation on each island, we selected two to three scenarios for each island, conducted a habitat representation analysis on two scenarios for each island, and present these as examples of potential trapping scenarios. Scenarios are presented as examples of effort and expected precision. With an understanding of the trade-offs presented in the example scenarios, managers can tailor one of these protocols to be used on their respective islands.

Changing population status may allow managers to reduce trapping effort. First, because precision scales with population size, precision goals may be reached with reduced effort at larger population sizes. Additionally, managers may desire to reduce precision targets as population status improves, such as when a population is large and has high survival. In these cases, reduced trapping may be desirable because of reduced cost and reduced risk of stress and disruption to foxes. In the case of multiple small trapping "units," this may be accomplished by reducing the number of units trapped on the island. Trap effort can, alternatively, be reduced by maintaining the same number of units and reducing the number of nights trapped. In addition to loss of precision, these decisions should consider labor and time saved by each option and the loss of habitat representation that will occur if units are removed.

Survival Monitoring

The risks of eagle predation and disease create the primary need for survival monitoring, as demonstrated by the near loss of subspecies on the northern islands (due to eagle predation) and on Santa Catalina Island (apparently due to disease). Because the detection of either eagle predation or disease would trigger management actions (e.g., eagle removal, vaccination, or capturing foxes for quarantine), survival monitoring must be continuous and occur in "real time," which requires frequent year-round monitoring of radiocollared animals on each island. These two risks influence the required number of collared animals and the frequency at which they need to be monitored.

Simulations suggest that an eagle-specific mortality rate of $\geq$2.5%, averaged over a 3-year period, can be detected if at least 40 radiocollared foxes are monitored frequently on each island. The Fox Health TEG advised that, ideally, the 40 animals should be checked every 24 hours; at a minimum, signals from the 40 animals should be monitored every 2-3 days in the winter months and every 1-2 days in the summer, as high temperatures can quickly deteriorate the condition of a carcass and compromise the ability to obtain meaningful necropsy results. Although less frequent monitoring (such as once per week) may be adequate for monitoring eagle predation (i.e., carcasses would likely be investigated rapidly enough to determine this cause of death), it would not be adequate for disease surveillance.

The choice of which 40 animals to collar is also an important decision, and we suggest the following guidelines:

1. Collared animals should be distributed across each island, rather than being clumped in one area, to best sample survival that may vary geographically and to detect disease outbreaks prior to spread.
2. Collared animals should represent all age classes.
3. Collared animals should include approximately equal numbers of males and females.
4. As suggested by the Fox Health TEG, animals monitored for survival should not be vaccinated against disease, as they should represent true sentinels for disease. The Fox Health TEG and population modelers recommend that a subset of animals on each island be vaccinated against rabies and canine distemper. The role of the 40 monitored animals is, therefore, to detect: (a) disease outbreaks other than rabies or distemper (i.e., diseases for which the population is not protected via vaccination), (b) a rabies or distemper outbreak so that unvaccinated animals could be vaccinated and that vaccine efficacy among vaccinated animals could be evaluated, and (c) other causes of mortality such as eagle kills, vehicular trauma, or dog attacks.

Ideally, a new set of 40 collars should be applied every year during annual census trapping, to maintain a sample of animals representative of the population and to reduce the chance of bias if the same cohort of animals is tracked for multiple years.

To facilitate monitoring collared animals at the suggested frequency, island managers should collaborate in evaluating the feasibility and cost-effectiveness of (a) aerial monitoring via plane or helicopter, through a joint contract of services, (b) monitoring via remote receivers, and (c) monitoring via GPS collars, with potential cost-savings for bulk purchase.

Data Management and Integration

Data generated from long-term monitoring are valuable for understanding factors influencing island fox populations. Monitoring is also intended to generate comparable data for comparisons and analyses across islands. It is therefore critical that data be collected, stored, and managed in a standardized manner that will allow for accurate and efficient use, both within and across islands.

To generate data useful for exploring the dynamics of fox populations, this monitoring should also include standardized and long-term collection of other biotic and abiotic data, such as:

- Climate and local weather patterns
- Abundance and distribution of other species
- Disease profiles among other species
- Vegetation characteristics
- Other environmental health parameters (e.g., road traffic, rodenticide use, human activities).

These data should be compiled and managed in a way that allows future integration and analyses with fox population data. To increase the usefulness of datasets, collection and management of data should be coordinated across islands.

Research Modules and Outstanding Questions

Recommendations presented in this report are part of an adaptive framework intended to provide the basis for future refinement of monitoring protocols. Refinements will be required over time as monitoring objectives and needs change, e.g., as population size and threats to foxes change over time, as our knowledge of fox ecology grows, and as new analytical techniques allow improvement of monitoring protocols.

Monitoring protocols outlined in this report will produce long-term standardized demographic data on island foxes which will provide a context for additional research on island fox biology, environmental factors affecting the viability and dynamics of fox populations, and management intervention. Research results may, in turn, be used to refine future monitoring protocols or analyses of monitoring data. In this report, we discuss several recommended research topics for each island. These include:

- Changes in vegetation communities and species composition
- Habitat and space use by foxes
- Fox community dynamics
- Disease and health
- Factors influencing fox survival
- Reproduction and early pup survival
- Ecological relationships with skunks and feral cats
- Effectiveness of remote telemetry stations and camera stations
- Analytical approaches, including indices of trend
- Surveys of human perspectives and education
- Impacts of traffic, rodenticide use, and nonnative herbivores

Through the collaborative process of developing this monitoring framework, several concepts and questions have emerged that warrant additional evaluation in the continuous quest to improve field protocols and analytical approaches and make conservation efforts more cost-effective. Some of these are outlined below.

1. What is the most cost-effective means of monitoring foxes for survival using known fate methods? This can include one or more of the following: ground monitoring, aerial monitoring, monitoring via remote receivers, monitoring of GPS collars. The choice will depend on a monetary cost analysis and an evaluation of the ever-improving technologies of GPS collars and remote receivers. For remote receivers, such an evaluation should include determining actual, in-field detection ranges for telemetry signals as a function of

terrain, location, and tower heights, and a viewshed analysis to determine the number and locations of towers needed to monitor the island adequately. Although the choice can be island-specific, the most efficient solution may result from coordinated exploration of options by managers of all islands.

2. What proportion of monitored animals should be vaccinated? The current recommendation is that monitored animals should not be vaccinated, allowing them to be true sentinels for disease outbreaks. However, the Fox Health TEG, with assistance from population modelers, has yet to determine the total number of animals to be vaccinated on each island. This decision will, in turn, dictate how many unvaccinated animals are available as sentinels. This is particularly important for small populations.
3. How does the presence of skunks influence the effectiveness and optimal design of trapping protocols? Recent trap data from Santa Rosa and Santa Cruz islands indicate an increase in trap success in capturing skunks. This reduces the availability of traps to foxes and has implications for the precision of estimates derived from trap data. Further research is needed to determine how to best account for this effect, and how the prior capture of a skunk influences subsequent capture of a fox in the same trap.
4. Can locational data from collared animals be used to provide additional options for analyzing trap data? A potential approach for estimating density with the use of radiocollared animals is to combine telemetry data with trapping data. Generally, this approach calls for delineating the area associated with a trapping unit, determining the proportion of locations within the trapping area for radiocollared 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.
5. Can trap protocols and analysis of trap data be improved with increased knowledge of fox behavior and movement patterns? 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 behavior 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 may account for such potential influences.

Beyond Recovery

Questions remain about the ecology and optimal sampling designs for island foxes. Their isolation, small population sizes, and apparent low historic exposure to disease, coupled with human-caused changes to their environments, mean that island foxes will always be vulnerable to extinction due to demographic and environmental stochasticity. Thus, robust monitoring of fox populations, while key to recovery of federally listed species, will also continue to be a necessary component of island management beyond recovery.

As a result of changing threats and status of island fox populations, and with the collection of additional data and continued collaborations, monitoring objectives and protocols may evolve and be adapted to obtain more cost-effective, useful, and robust information. We hope the data that is generated from these monitoring programs will stimulate further research that contributes to the management of this species.

A Population Monitoring Framework
for Five Subspecies of Island Fox
(*Urocyon littoralis*)

Prepared for

The Recovery Coordination Group
of the
Island Fox Integrated Recovery Team

Prepared by

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Brian S. Cohen[4], Jerre A. Stallcup[1], Wayne D. Spencer[1],
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Acknowledgements

This document was developed in response to the Technical Analysis Request (TAR) 2.1 issued by the Recovery Coordination Group (RCG) of the Channel Islands Fox Integrated Recovery Team (Recovery Team). It represents the effort of the Monitoring Task Force, formed in response to TAR 2.1, to develop island-specific monitoring protocols for review by the Population Modeling Technical Expertise Group (TEG), Wild Population Management TEG, and Fox Health TEG, as well as land managers of the Channel Islands. As such, this framework reflects a culmination of years of investigation, discussion, and planning by the Recovery Team, its many dedicated participants, and all who have contributed to the understanding of this species.

The following scientific advisors contributed specific analyses and guidance critical to developing the monitoring framework: Deanna Clifford, U.C. Davis; Dan Doak, U.C. Santa Cruz; Linda Munson, U.C. Davis; Eric Rexstad, University of St. Andrews, Scotland; Andy Royle, USGS Patuxent Wildlife Research Center; and Winston Vickers, Institute for Wildlife Studies (IWS).

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Finally, we thank The Nature Conservancy and the Santa Catalina Island Conservancy for providing the funding to develop a monitoring framework that is foundational to the recovery and management of this species. And we are grateful for the leadership of Kelly Brock and the U.S. Navy, for commissioning an earlier monitoring planning effort for San Clemente Island Fox; that process and analysis provided an important foundation for the work presented here.

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- Disease and health profiles, as sampled from all dead foxes and from a subset of the living population, based on sampling protocols determined by the Fox Health TEG (all islands).

Population Sampling Considerations

Experts involved in developing a previous island fox monitoring framework for the U.S. Navy on San Clemente Island recommended trapping and radio telemetry as key components for islandwide fox monitoring to address mortality rates and causes. Trapping also provides the best means of estimating population sizes with known precision and confidence intervals. The use of GPS collars provides an additional means of monitoring habitat use and, possibly, mortality. To minimize stress to foxes, as well as labor and equipment costs, we recommend scenarios in which both these objectives may, for the most part, be met with one annual trapping effort, thereby making the best use of personnel resources and reducing disruption to foxes that might occur from multiple trapping efforts.

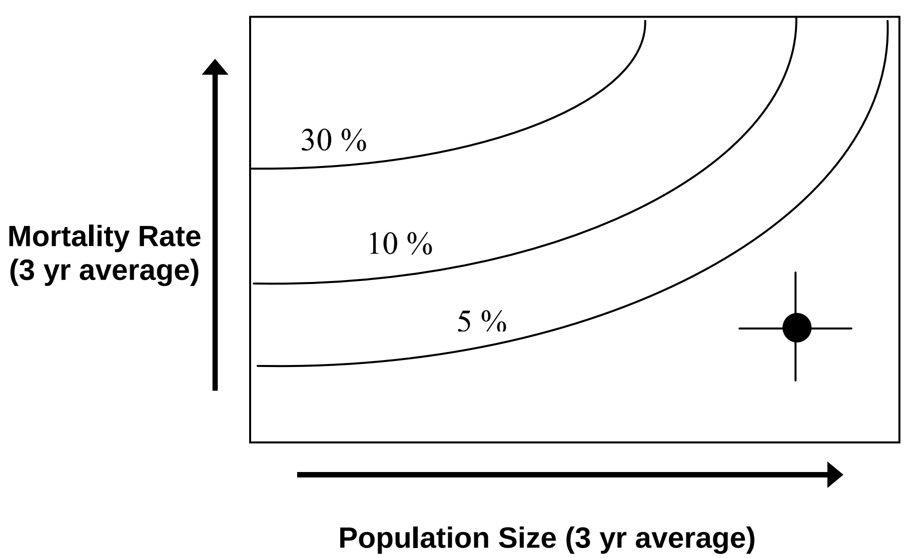
In determining specific trapping protocols, we considered a wide range of factors, including the ecology and behavior of the species, the logistical constraints on each island, and the selection of feasible monitoring methods that can provide the desired measurements in the most efficient and statistically robust manner. For island foxes, some key biological issues are their social structure (and existence of territories held by monogamous pairs), their ability to inhabit essentially every habitat type on the islands, and the timing of parturition. Access constraints on the islands, and concern for animal welfare, limit the choice and design of sampling protocols. Steep and rugged terrain, primitive road conditions or lack of roads, and large size of three of the islands make the use of large trapping grids infeasible, and ecologically sensitive areas seasonally restrict access to some areas for trapping.

The choice of trapping protocols involves tradeoffs between desired precision, feasibility and cost, and the extent of trapping; these, in turn, are influenced by the status of the population. For large populations with high survival, the risk of quasi-extinction is low; that is, these populations lie far from the 5% quasi-extinction isocline (Box ES-1). High precision in population estimates may be less important in such cases, compared to populations with smaller N and/or higher mortality, and managers may choose to reduce the extent of trapping and subsequently generate population estimates with lower precision (i.e., with CV >20%), thereby reducing costs, efforts, and potential risk and stress to foxes.

Our goal was to identify feasible trapping approaches for each island that would generate a statistically robust estimate with adequate precision and representation of island habitats. We provide recommended monitoring protocols that strive to estimate population size with a coefficient of variation (CV) of ≤20% when feasible. CV($\hat{N}$) is a measure of precision equal to the standard error of the estimate divided by the estimate itself. There is flexibility in the required precision of trend, and this level of precision will ultimately be decided by island managers, in their decision on trapping protocols. Although one standardized sampling approach across all islands would have been desirable, objectives and constraints differ somewhat across islands. Therefore, island-specific protocols must be tailored accordingly. The key parameters obtained from trapping should nevertheless be comparable among islands.

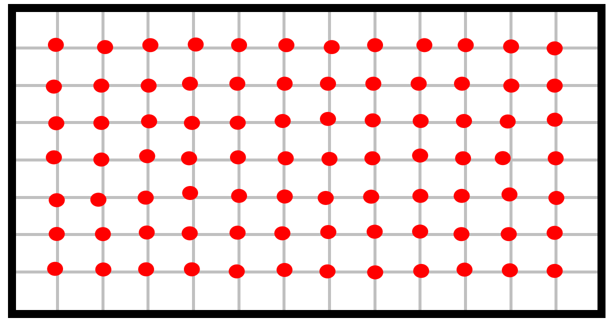
Box ES-1. Example of risk isoclines, with the status of a hypothetical population plotted.

The combination of a population's 3-year average size and mortality rate can be plotted to determine the population's status in relation to predetermined risk isoclines (shown here as 5, 10, and 30% risk isoclines). In this case, the population's status (shown as a point estimate along with 80% confidence intervals) is well below the isocline representing a 5% risk of quasi-extinction over 50 years, indicating a low level of risk.

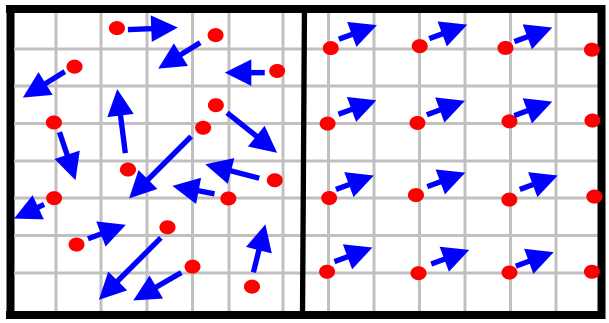


We considered five trapping approaches and configurations expected to provide robust parameter estimation for population size (and therefore also for trend):

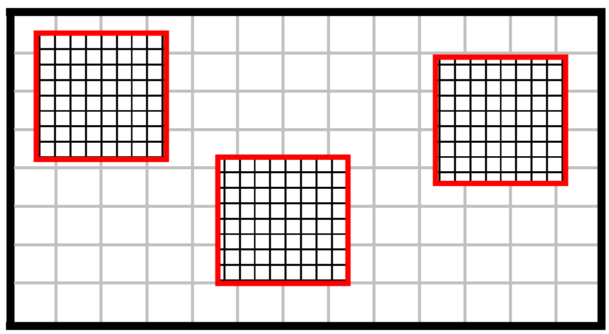
1. Island-wide systematic trapping. This was an option explored for San Clemente Island, in which traps are placed systematically and evenly on the island, <600 meters apart to allow for equal capture probability among all foxes. Population estimates are generated via mark-recapture methods with the entire island considered the effective trap area.



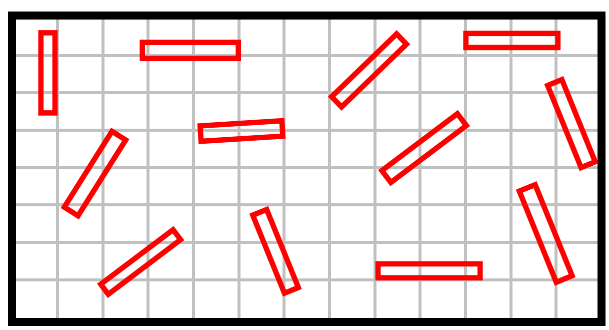
2. Island-wide random trapping. Traps are placed randomly or systematically on a grid (with ≤1200-meter spacing) and moved to new random locations individually or randomly as a shifted grid (up to ½ inter-trap distance), respectively, before each trapping occasion. Population estimates are generated via mark-recapture methods with the entire island considered the effective trap area.



3. Traditional trapping grids. Population size is extrapolated from local grid densities, based on (a) mark-recapture estimates of local abundance in combination with estimated local effective trap area (from distances moved by recaptured animals) or (b) spatially explicit capture-recapture methods, using movement and detection patterns alone.



4. Multiple small trapping "units." Population size is extrapolated from local units via spatially-explicit capture-recapture methods. Traditional mark-recapture methods cannot yield precise density estimates for transect-shaped units due to edge effects.



Island-wide systematic trapping is not feasible due to the large number of traps that would be necessary. We did not consider linear transect trapping, protocols currently used on Santa Catalina and Santa Cruz islands, because there is no statistically valid method for estimating the effective trap area around transects from trap data, thereby making it difficult to estimate density. We used simulation and analyses to examine and compare expected precision of other trapping configurations and protocols (e.g., number of traps, number of nights trapped). To account for spatial heterogeneity in local densities, we focused on protocols that use statistically rigorous sampling design, with trap layout determined by random, stratified, or systematic with random origin placement. For each island, we examined various trapping scenarios for expected precision, required field effort, and likely representation of habitat variability on the island, and compared them with required effort, statistical robustness, and representation of habitat variability of existing protocols.

Recognizing trade-offs between effort, feasibility, and the desire to maximize precision and habitat representation on each island, we selected two to three scenarios for each island, conducted a habitat representation analysis on two scenarios for each island, and present these as examples of potential trapping scenarios. Scenarios are presented as examples of effort and expected precision. With an understanding of the trade-offs presented in the example scenarios, managers can tailor one of these protocols to be used on their respective islands.

Changing population status may allow managers to reduce trapping effort. First, because precision scales with population size, precision goals may be reached with reduced effort at larger population sizes. Additionally, managers may desire to reduce precision targets as population status improves, such as when a population is large and has high survival. In these cases, reduced trapping may be desirable because of reduced cost and reduced risk of stress and disruption to foxes. In the case of multiple small trapping "units," this may be accomplished by reducing the number of units trapped on the island. Trap effort can, alternatively, be reduced by maintaining the same number of units and reducing the number of nights trapped. In addition to loss of precision, these decisions should consider labor and time saved by each option and the loss of habitat representation that will occur if units are removed.

Survival Monitoring

The risks of eagle predation and disease create the primary need for survival monitoring, as demonstrated by the near loss of subspecies on the northern islands (due to eagle predation) and on Santa Catalina Island (apparently due to disease). Because the detection of either eagle predation or disease would trigger management actions (e.g., eagle removal, vaccination, or capturing foxes for quarantine), survival monitoring must be continuous and occur in "real time," which requires frequent year-round monitoring of radiocollared animals on each island. These two risks influence the required number of collared animals and the frequency at which they need to be monitored.

Simulations suggest that an eagle-specific mortality rate of $\geq$2.5%, averaged over a 3-year period, can be detected if at least 40 radiocollared foxes are monitored frequently on each island. The Fox Health TEG advised that, ideally, the 40 animals should be checked every 24 hours; at a minimum, signals from the 40 animals should be monitored every 2-3 days in the winter months and every 1-2 days in the summer, as high temperatures can quickly deteriorate the condition of a carcass and compromise the ability to obtain meaningful necropsy results. Although less frequent monitoring (such as once per week) may be adequate for monitoring eagle predation (i.e., carcasses would likely be investigated rapidly enough to determine this cause of death), it would not be adequate for disease surveillance.

The choice of which 40 animals to collar is also an important decision, and we suggest the following guidelines:

1. Collared animals should be distributed across each island, rather than being clumped in one area, to best sample survival that may vary geographically and to detect disease outbreaks prior to spread.
2. Collared animals should represent all age classes.
3. Collared animals should include approximately equal numbers of males and females.
4. As suggested by the Fox Health TEG, animals monitored for survival should not be vaccinated against disease, as they should represent true sentinels for disease. The Fox Health TEG and population modelers recommend that a subset of animals on each island be vaccinated against rabies and canine distemper. The role of the 40 monitored animals is, therefore, to detect: (a) disease outbreaks other than rabies or distemper (i.e., diseases for which the population is not protected via vaccination), (b) a rabies or distemper outbreak so that unvaccinated animals could be vaccinated and that vaccine efficacy among vaccinated animals could be evaluated, and (c) other causes of mortality such as eagle kills, vehicular trauma, or dog attacks.

Ideally, a new set of 40 collars should be applied every year during annual census trapping, to maintain a sample of animals representative of the population and to reduce the chance of bias if the same cohort of animals is tracked for multiple years.

To facilitate monitoring collared animals at the suggested frequency, island managers should collaborate in evaluating the feasibility and cost-effectiveness of (a) aerial monitoring via plane or helicopter, through a joint contract of services, (b) monitoring via remote receivers, and (c) monitoring via GPS collars, with potential cost-savings for bulk purchase.

Data Management and Integration

Data generated from long-term monitoring are valuable for understanding factors influencing island fox populations. Monitoring is also intended to generate comparable data for comparisons and analyses across islands. It is therefore critical that data be collected, stored, and managed in a standardized manner that will allow for accurate and efficient use, both within and across islands.

To generate data useful for exploring the dynamics of fox populations, this monitoring should also include standardized and long-term collection of other biotic and abiotic data, such as:

- Climate and local weather patterns
- Abundance and distribution of other species
- Disease profiles among other species
- Vegetation characteristics
- Other environmental health parameters (e.g., road traffic, rodenticide use, human activities).

These data should be compiled and managed in a way that allows future integration and analyses with fox population data. To increase the usefulness of datasets, collection and management of data should be coordinated across islands.

Research Modules and Outstanding Questions

Recommendations presented in this report are part of an adaptive framework intended to provide the basis for future refinement of monitoring protocols. Refinements will be required over time as monitoring objectives and needs change, e.g., as population size and threats to foxes change over time, as our knowledge of fox ecology grows, and as new analytical techniques allow improvement of monitoring protocols.

Monitoring protocols outlined in this report will produce long-term standardized demographic data on island foxes which will provide a context for additional research on island fox biology, environmental factors affecting the viability and dynamics of fox populations, and management intervention. Research results may, in turn, be used to refine future monitoring protocols or analyses of monitoring data. In this report, we discuss several recommended research topics for each island. These include:

- Changes in vegetation communities and species composition
- Habitat and space use by foxes
- Fox community dynamics
- Disease and health
- Factors influencing fox survival
- Reproduction and early pup survival
- Ecological relationships with skunks and feral cats
- Effectiveness of remote telemetry stations and camera stations
- Analytical approaches, including indices of trend
- Surveys of human perspectives and education
- Impacts of traffic, rodenticide use, and nonnative herbivores

Through the collaborative process of developing this monitoring framework, several concepts and questions have emerged that warrant additional evaluation in the continuous quest to improve field protocols and analytical approaches and make conservation efforts more cost-effective. Some of these are outlined below.

1. <u>What is the most cost-effective means of monitoring foxes for survival using known fate methods</u>? This can include one or more of the following: ground monitoring, aerial monitoring, monitoring via remote receivers, monitoring of GPS collars. The choice will depend on a monetary cost analysis and an evaluation of the ever-improving technologies of GPS collars and remote receivers. For remote receivers, such an evaluation should include determining actual, in-field detection ranges for telemetry signals as a function of

terrain, location, and tower heights, and a viewshed analysis to determine the number and locations of towers needed to monitor the island adequately. Although the choice can be island-specific, the most efficient solution may result from coordinated exploration of options by managers of all islands.

2. What proportion of monitored animals should be vaccinated? The current recommendation is that monitored animals should not be vaccinated, allowing them to be true sentinels for disease outbreaks. However, the Fox Health TEG, with assistance from population modelers, has yet to determine the total number of animals to be vaccinated on each island. This decision will, in turn, dictate how many unvaccinated animals are available as sentinels. This is particularly important for small populations.

3. How does the presence of skunks influence the effectiveness and optimal design of trapping protocols? Recent trap data from Santa Rosa and Santa Cruz islands indicate an increase in trap success in capturing skunks. This reduces the availability of traps to foxes and has implications for the precision of estimates derived from trap data. Further research is needed to determine how to best account for this effect, and how the prior capture of a skunk influences subsequent capture of a fox in the same trap.

4. Can locational data from collared animals be used to provide additional options for analyzing trap data? A potential approach for estimating density with the use of radiocollared animals is to combine telemetry data with trapping data. Generally, this approach calls for delineating the area associated with a trapping unit, determining the proportion of locations within the trapping area for radiocollared 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.

5. Can trap protocols and analysis of trap data be improved with increased knowledge of fox behavior and movement patterns? 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 behavior 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 may account for such potential influences.

Beyond Recovery

Questions remain about the ecology and optimal sampling designs for island foxes. Their isolation, small population sizes, and apparent low historic exposure to disease, coupled with human-caused changes to their environments, mean that island foxes will always be vulnerable to extinction due to demographic and environmental stochasticity. Thus, robust monitoring of fox populations, while key to recovery of federally listed species, will also continue to be a necessary component of island management beyond recovery.

As a result of changing threats and status of island fox populations, and with the collection of additional data and continued collaborations, monitoring objectives and protocols may evolve and be adapted to obtain more cost-effective, useful, and robust information. We hope the data that is generated from these monitoring programs will stimulate further research that contributes to the management of this species.

1 Introduction

This document presents monitoring plans for island foxes (*Urocyon littoralis*) on five Channel Islands off the coast of southern California: San Miguel, San Nicolas, Santa Catalina, Santa Rosa, and Santa Cruz (Map 1-1). It represents a collaborative effort among members of the Channel Island Fox Integrated Recovery Team, members of its Recovery Coordination Group (RCG), island managers, technical experts, population modelers, veterinarians, and others, and builds on an impressive knowledge base from years of monitoring and research by island fox experts. Sections 1-3 describe the considerations and approaches used to identify specific monitoring needs (objectives), determine parameters to address these objectives, and develop protocols to measure these parameters. Sections 4-8 recommend monitoring protocols and potential research topics for each island (sections are ordered by island size, from smallest to largest). We offer these recommendations as guidelines with some built-in flexibility to account for on-the-ground feasibility. For example, we provide at least two alternative trapping scenarios for each island, and for each scenario we provide information on expected precision (e.g., for resulting population estimates), effort required, and estimated habitat representation. Our intent is to provide island managers with a range of examples, which they can choose from or modify as needed, based on their resources and priorities, understanding that there is generally a tradeoff between monitoring intensity and information value. So although we present specific trapping scenarios, island managers must adapt these for on-the-ground use. We also recognize that questions remain about the ecology and optimal sampling designs for this species. As a result of changing threats and status of island fox populations, and with the collection of additional data, monitoring objectives may evolve and protocols may be adapted to obtain more cost-effective, useful, and robust information. We suggest that monitoring protocols be reviewed and refined as additional information or monitoring techniques become available.

1.1 Background

1.1.1 Status of Channel Island Foxes

Island foxes inhabit the six largest Channel Islands off the coast of southern California (Table 1-1, Map 1-1), with a separate subspecies recognized on each island. Due to their limited geographic distribution and small population sizes, island foxes on all six islands have been listed as Threatened by the State of California since 1971 [California Department of Fish and Game (CDFG) 1987]. In 2004, the U.S. Fish and Wildlife Service (USFWS) listed the San Miguel Island Fox (*U. l. littoralis*), Santa Catalina Island Fox (*U. l. catalinae*), Santa Rosa Island Fox (*U. l. santarosae*), and Santa Cruz Island Fox (*U. l. santacruzae*) as Endangered due to recent precipitous population declines and high risk of extinction (USFWS 2004). The San Clemente Island Fox (*U. l. clementae*) and San Nicolas Island Fox (*U. l. dickeyi*) are not federally listed but are protected under California law.

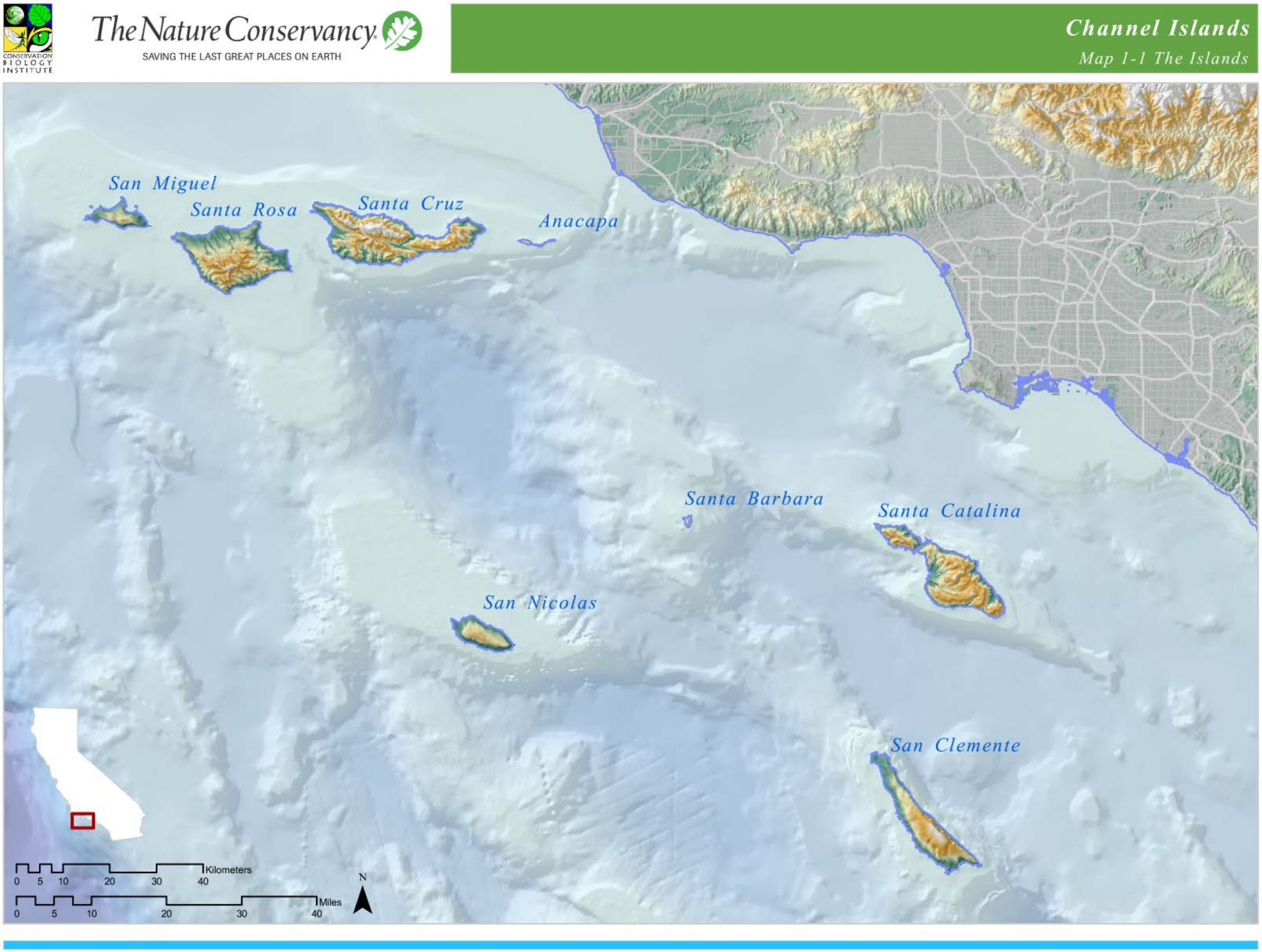

The Nature Conservancy
SAVING THE LAST GREAT PLACES ON EARTH
CONSERVATION BIOLOGY INSTITUTE
Channel Islands
Map 1-1 The Islands
San Miguel
Santa Rosa
Santa Cruz
Anacapa
Santa Barbara
Santa Catalina
San Nicolas
San Clemente
Kilometers
0 5 10 20 30 40
Miles
0 5 10 20 30 40
N

Table 1-1. Channel Islands of California: size and distance from the mainland.

Island	Island Size (km^2)	Distance to Mainland (km)
Anacapa Island[1]	3	21
Santa Barbara Island[1]	3	61
San Miguel Island	36	42
San Nicolas Island	58	98
San Clemente Island	145	66
Santa Catalina Island	194	32
Santa Rosa Island	218	44
Santa Cruz Island	249	31

[1] Island not inhabited by island foxes.

1.1.2 Island Foxes as an *At Risk* Island Species

Because their size is restricted by the size of the land masses they occupy, island populations are often smaller than their mainland counterparts, and small populations are at increased risk of extinction due to demographic and environmental stochasticity (Lande 1993). In the event of a declining population, the chance of natural population augmentation or a "rescue effect" (Brown and Kodric-Brown 1977) via immigration from neighboring populations is extremely small for a terrestrial mammalian population living on an island. This increased risk of extinction for island species may be magnified for carnivores such as island foxes, because carnivores are generally found at low densities compared to similar-sized non-predatory species (Colinvaux 1978). Island foxes are especially vulnerable to catastrophes caused by introduction of nonnative predators (e.g., golden eagles), nonnative competitors and disease vectors (e.g., domestic cats and dogs), and alteration of their habitat (e.g., by introduced livestock). Due to their long history of small population size and isolation on distant islands, island foxes may also be at increased risk due to low genetic diversity and apparent low historic exposure to disease (Wayne et al. 1991, Garcelon et al. 1992). For these reasons, island foxes can be considered a species that is naturally and perpetually at risk.

Foxes on each of the six islands have been negatively impacted by human activities, either directly or indirectly. Habitat on all islands occupied by foxes has been altered by livestock grazing, introduction of nonnative ungulates, and the spread of nonnative plants. Island fox populations have also been negatively impacted by predation by golden eagles (*Aquila chrysaetos)* on San Miguel, Santa Rosa, and Santa Cruz islands and by disease on Santa Catalina Island, resulting in catastrophic population declines (Roemer et al. 2004). Captive breeding programs and subsequent releases of captive-bred animals, in combination with continuing efforts to remove golden eagles, have thus far prevented the extinction of these foxes (Coonan 2003). Despite these efforts, however, island foxes remain at high risk.

Due to this persistent high risk, robust monitoring of fox populations and threats to foxes is a key component of recovery for federally listed foxes, as well as a necessary management component for unlisted foxes.

1.1.3 Monitoring Planning Process

Monitoring of Channel Island foxes has been conducted for a number of years by various methods on the six Channel Islands supporting foxes. However, methods have varied among islands and among years. For example, population data have been collected via grid trapping on some islands and transect trapping on other islands, at times combined with other field activities such as targeted trapping (e.g., to target specific individuals in specific areas), tracking of radiocollared animals, and camera monitoring. However, many of the existing field protocols were not initially developed for the purpose of long-term monitoring, but rather to provide near-term assessment of population status on individual islands. As a result, existing field protocols may not be as efficient as they could be, and may not be effective in addressing current monitoring objectives. For example, annual trapping efforts on Santa Catalina and Santa Cruz islands have been so extensive in past years that they approach island-wide censuses rather than population sampling efforts. It is possible that protocols could be more efficient, so that limited resources are available for other monitoring, management, or research activities. In addition, field protocols have not been coordinated among islands to produce comparable data. For example, data on reproduction and recruitment have not been collected at the same time of year on each island. Lastly, a number of field protocols were designed without the benefit of currently existing data, which can now be used to refine and improve sampling protocols. Fortunately, data archives from the many years of field work on the various islands now provide the resource necessary for designing plans that optimize information return on monitoring investment.

In an effort to develop robust and efficient monitoring protocols, a multi-year and highly collaborative monitoring planning process was undertaken. Key milestones of that process included:

1. Compilation and analysis of population data by V. Bakker and collaborators to estimate demographic parameters. Managers and researchers from multiple islands contributed data to this collaborative effort, which represented the first comprehensive synthesis of monitoring data across islands.
2. Development of a population viability analysis (PVA) by D. Doak and collaborators, and a PVA experts workshop at the National Center for Ecological Analysis and Synthesis, which provided much of the conceptual framework for understanding fox demographics and threats to fox viability.
3. Development of a set of guidelines by the Island Fox Health Technical Expertise Group (TEG; chaired by L. Munson, UC Davis), which outlines recommendations for wild fox health monitoring. That document provides guidelines on vaccination protocols, collection of health data, and future research needs related to fox health.
4. Development of a proposed monitoring plan for island foxes on San Clemente Island (Spencer et al. 2006). This process involved the review of previous monitoring protocols and resulting data, a workshop with experts, and statistical analyses of existing and proposed monitoring protocols for San Clemente Island.

5. Issuance by the RCG of Technical Analysis Request (TAR) 2.1 "Development of Population Monitoring Plans for Free-Ranging Island Foxes." The goals of the TAR were to:
   - Assess management objectives for fox populations on each island and recommend monitoring protocols designed specifically to address these management needs.
   - Recommend monitoring protocols to collect population parameters for refining PVAs that may be used to guide management.
   - Recommend monitoring protocols to collect population parameters necessary to determine if recovery criteria, as will be defined in the USFWS Recovery Plan, are being achieved[1].
   - Recommend monitoring protocols to collect population parameters necessary for cross-island comparisons to increase our knowledge about island fox population dynamics.
   - Recommend topics for future research studies which, although not part of a long-term monitoring plan, may complement long-term monitoring activities.
   - Facilitate collection of animal health data to track population health per the recommendation of the Fox Health TEG.

   The TAR further specified that the following TEGs should help develop and review the monitoring plans: Population Modeling TEG, Wild Population Management TEG, and Fox Health TEG.
6. Commissioning the Conservation Biology Institute (CBI) to coordinate the development of island-specific monitoring protocols, with the assistance of V. Bakker and M. Efford. E. Rubin of CBI was named chair of the Monitoring Task Force formed in response to TAR 2.1.
7. Presentation and review of the Monitoring Task Force's framework monitoring approach at the second PVA workshop at the University of California, Davis, December 2006.

The TAR suggested that the following general steps and analyses should be followed to develop the protocols for each island:

1. Collect and review information pertinent to each island, including past and current monitoring programs, monitoring data, and ecological and physical characteristics of the islands as they relate to monitoring needs and constraints.
2. Identify and articulate monitoring objectives using input from managers and the TEGs.
3. Evaluate whether existing protocols are generating the parameter estimates needed to meet current monitoring objectives. For example, a representation analysis of trapping protocols should be conducted to determine how well trapping efforts are sampling the range of habitat variability on an island (e.g., vegetation, topography, distance to shoreline) and management issues (e.g., distance to roads) on the island.

[1] The USFWS Recovery Plan for island foxes is currently being prepared.

4. Develop recommended protocols, possibly with alternative scenarios (e.g., variations in trapping protocols that are offered as feasible options for each island), to collect data on fox survivorship, cause-specific mortality, and demography.
5. Obtain input from managers and the Task Force on the above protocols and alternative scenarios to determine feasibility and efficacy in estimating desired parameters.
6. Obtain input from a statistician on the above protocols and alternative scenarios to determine if methods are statistically robust.
7. Conduct representation analysis on recommended sampling (trapping) alternatives to determine how well they represent habitat variability (e.g., vegetation, topography, distance to shoreline) and management issues (e.g., distance to roads) on the island.
8. Prepare draft and final monitoring plans for each island, allowing time for review and input from managers and the Task Force.

1.2 Monitoring Objectives

Monitoring data can provide valuable information for wildlife conservation and management. Monitoring objectives dictate the type and precision of data to be collected which, in turn, determine the appropriate monitoring protocols. To identify appropriate objectives to be addressed by long-term monitoring of Channel Island foxes, we solicited input from island managers, TEGs, and the RCG. Using this input, it was determined that an effective monitoring plan should address each of the following general objectives:

1. Track recovery of fox populations relative to recovery criteria which will be defined in the USFWS Recovery Plan for this species.
2. Determine when delisting is warranted (as will be defined in the USFWS Recovery Plan).
3. Guide island-specific management decisions such as those related to captive breeding, vaccination, eagle removal, and management of human activities.
4. Refine parameter estimates for population viability analyses and facilitate other cross-island comparisons.

We also sought affordability, and this will require tradeoffs. We note that the list above represents only a subset of the questions related to foxes that we need or may want to address through monitoring and research. The express aim of this monitoring program was to identify the essential core of information in which managers should invest. That investment not only provides information to track and manage the population status, but it may also provide incentives for others to embark on independent or sponsored research programs that add to this foundational dataset. We provide examples of potential research topics in each island-specific chapter.

2 Monitoring Parameters and Approach

2.1 Identification and Prioritization of Parameters

A monitoring plan for island fox populations must address multiple objectives based on varying needs. To ensure that all objectives and needs were addressed by this framework, we solicited input from island managers, biologists, population modelers, TEGs, and the RCG. Island managers identified and prioritized monitoring needs related to island-specific management objectives (Table 2-1).

This framework incorporates the general philosophy of the RCG, which emphasizes close tracking of fox mortality rates to identify the presence and intensity of the fox's primary threats, namely eagle predation and disease, and to rapidly detect new threats. Precise and fine temporal-scale knowledge of mortality is vital for triggering management action to control these threats. Mortality rates, especially for adults, exert the greatest influence on the risk of extinction for island foxes in population viability analyses (Miller et al. 2003, Kohlmann et al. 2005, Bakker et al. In review), and observed mortality rates can be used to accurately predict future risk (D. Doak, University of Santa Cruz, pers. comm.). Population size estimates and general trends in abundance can help corroborate conclusions regarding population status made from mortality data, and population size estimates improve risk predictions from mortality data (D. Doak, University of Santa Cruz, pers. comm.). While other philosophical approaches emphasize precise estimates of population size and abundance trends, our reliance on mortality rates derives from the commitment to monitor mortality precisely and the relationship between mortality rates and population status.

Based on this general philosophy, management goals of island managers, and further input from population modelers and TEGs, the following monitoring parameters were identified as those to be targeted in monitoring protocols for the purpose of tracking and determining recovery:

- Mortality rates at high precision (with associated cause-specific mortality rates).
- Population trend (or lambda [λ]) at low to moderate precision. This may be estimated from annual population estimates or from population models.
- Population size relative to a required minimum population size, as informed by PVA.

These parameters were discussed with the RCG and population modelers in relation to potential recovery criteria, information needed for population viability analyses, and precision goals.

Table 2-1. Monitoring goals for each island as stated and prioritized by island managers.

Island	Management goal:	Parameter needed:
San Miguel	1. Monitor population status and trend.	1. Index of island-wide changes in abundance (annual change in island-wide N or density)
	2. Monitor threats to population (influences on population size and viability).	2a. Survival (by age, sex, year) 2b. Cause-specific mortality (predation, disease, etc.) 2c. Reproduction (annual recruitment)
San Nicolas	**Management goal:**	**Parameter needed:**
	1. Estimate population size.	1. Island-wide abundance estimate (N)
	2. Monitor population status and trend.	2. Index of island-wide changes in abundance (annual estimate of island-wide N or density)
	3. Monitor threats to population (influences on pop size and viability).	3a. Survival (by age, sex, year) 3b. Cause-specific mortality (predation, disease, etc.)
	4. Inform land management decisions.	4. Density by habitat type
Santa Catalina	**Management goal:**	**Parameter needed:**
	1. Monitor threats to population (influences on population size and viability).	1a. Survival (by age, sex, year) 1b. Cause-specific mortality (predation, disease, etc.)
	2. Monitor population status and trend.	2. Index of island-wide changes in abundance (annual change in island-wide N or density)
	3. Estimate population size	3. Island-wide abundance estimate (N)
Santa Rosa	**Management goal:**	**Parameter needed:**
	1. Monitor population status and trend.	1. Index of island-wide changes in abundance (annual change in island-wide N or density)
	2. Monitor threats to population (influences on population size and viability).	2a. Survival (by age, sex, year) 2b. Cause-specific mortality (predation, disease, etc.) 2c. Reproduction (annual recruitment)
	3. Inform land management decisions.	3. Density by habitat type
Santa Cruz	**Management goal:**	**Parameter needed:**
	1. Monitor threats to population (influences on population size and viability).	1a. Survival (by age, sex, year) 1b. Cause-specific mortality (predation, disease, etc.)
	2. Monitor population status and trend.	2. Index of island-wide changes in abundance (annual change in island-wide N or density)
	3. Inform land management decisions.	3. Survival and density by habitat type

2.1.1 Parameters for Tracking Recovery

The following parameters were chosen to track recovery:

- Annual estimate of mortality and associated cause-specific mortality rates sufficient to detect an annual eagle-specific mortality rate of 2.5% or greater.[2] In addition, these data should provide information on disease and will facilitate health research.
- Annual estimate of island-wide population size, presented with an 80% confidence interval.
- Estimate of trend in population size. This estimate has no targeted precision; rather the precision will be determined by the precision of population estimates.

The above parameters were chosen to facilitate the evaluation of population status in relation to proposed recovery criteria. In anticipation of a recovery plan for the island fox, the RCG, land managers, and population modelers identified a set of proposed recovery criteria during the second PVA workshop, at the University of California, Davis, in December 2006. In relation to monitoring, the core parameters of the proposed criteria are:

1. An island fox population must have no more than 5% risk of quasi-extinction over a 50-year period. This risk level must be based on the following:
   - The risk of extinction must be calculated based on the lower 80% confidence interval for a 3-year average of population size estimates and the upper 80% confidence interval of a 3-year average of mortality rate estimates.
   - This risk level must be sustained for at least 5 years.
   - Quasi-extinction is defined as a population size of ≤30 individuals.
2. An island fox population trend must be increasing so that the average population estimate in year 5 is greater than that of year 1.
3. A golden eagle management strategy, approved by the land manager(s) charged with the recovery of an island fox population, must include monitoring protocols able to detect an annual island fox mortality rate caused by golden eagle predation of 2.5% or greater, averaged over 3 years.

Bakker et al. (In Review) developed models to assess the risk of quasi-extinction over a 50-year time period. Based on the model simulations, one can estimate the risk of a population reaching quasi-extinction using adult mortality rate and adult population size. These risk predictions can be plotted as isoclines, with each isocline identifying the risk of the population reaching the determined quasi-extinction level of 30 foxes over the determined timeframe of 50 years for different demographic conditions.

Assessment of the current predicted risk of quasi-extinction using isoclines relies on two parameters: the average adult mortality rate and the average adult population size calculated over

[2] Based on model simulations conducted and presented by D. Doak and V. Bakker, participants at the second PVA workshop, held at the University of California, Davis, in December 2006, determined that the ability to detect and respond to any eagle-specific mortality would be necessary to assure effective response to the presence of eagles. One eagle is expected to cause an annual mortality rate of 2.5%.

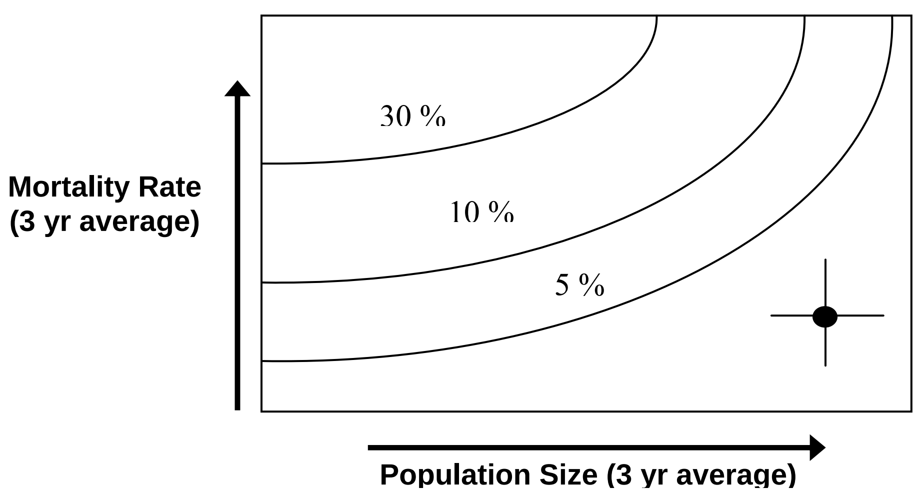
3 years. Status of the population in relation to a 5% risk of quasi-extinction is, therefore, based on a combination of these two parameters, with adult mortality having a greater influence on risk than population size.

These proposed recovery criteria, together with the RCG philosophy, influenced the targeted precision of protocols in this framework, i.e., high precision in mortality rates but greater flexibility in precision of population and trend estimates. This framework provides protocols that estimate true population size (N), with an estimate indicated by a "hat" ($\hat{N}$). Although not specified by managers or required by proposed recovery criteria, we recommend monitoring protocols that strive to estimate population size with a coefficient of variation (CV) of ≤20% when feasible. With respect to a population size estimate, CV($\hat{N}$) is a measure of precision equal to the standard error of the estimate divided by the estimate itself. A CV of <25% has been recommended for management purposes, while a CV <10% is generally considered necessary for research, and a CV of 50% is considered sufficient for pilot studies (Diefenbach and Mahan 2002). The level of precision for trend estimates will ultimately be decided by the managers in their decision on trapping protocols, which will determine precision of $\hat{N}$.

The choice of trapping protocols will involve tradeoffs between desired precision, feasibility and cost, and the extent of trapping; these, in turn, will be influenced by the status of the population. For large populations with high survival, the risk of quasi-extinction is low; that is, these populations lie far from the 5% quasi-extinction isocline (Box 2-1). High precision in population estimates may be less important in such cases, compared to populations with smaller N and/or higher mortality, and managers may choose to reduce the extent of trapping and subsequently generate population estimates with lower precision (i.e., with CV >20%), thereby reducing costs, efforts, and potential risk and stress to foxes.

Box 2-1. Example of risk isoclines, with the status of a hypothetical population plotted.

The combination of a population's 3-year average size and mortality rate can be plotted to determine the population's status in relation to predetermined risk isoclines (shown here as 5, 10, and 30 % risk isoclines). In this case, the population's status (shown as a point estimate along with 80% confidence intervals) is well below the isocline representing a 5% risk of quasi-extinction over 50 years, indicating a low level of risk.



2.1.2 Additional Parameters to Guide Fox Management Decisions

In addition to parameters identified specifically for tracking and determining recovery, the following additional parameters were identified by individual island managers as information needed to guide their fox management decisions (Table 2-1):

- Overall and cause-specific mortality rates by age and sex, to examine all causes of mortality (all islands).
- Habitat-specific density (San Nicolas, Santa Rosa, Santa Cruz).
- Habitat-specific survival (Santa Cruz Island).
- Reproduction measured in terms of annual recruitment (San Miguel, Santa Rosa).
- Disease and health profiles, as sampled from all dead foxes and from a subset of the living population based on sampling protocols determined by the Fox Health TEG (all islands).

Although all of the above parameters are of general management interest on all islands, several of them have been identified as priorities by some island managers.

2.1.3 Threats Monitoring

Monitoring threats will allow managers to better understand how fox populations are impacted by existing threats, so they can take management actions to reduce these threats, for example, removing golden eagles or capture and quarantine of foxes in the event of a disease outbreak. The following list provides examples of how monitoring will address such threats, as described in the USFWS's final rule for listing (USFWS 2004):

1. Present or threatened destruction, modification, or curtailment of fox habitat or range. Monitoring habitat- and site-specific density will improve our understanding of how habitat changes may impact fox population dynamics. For example, density could be compared in habitats far and near from paved roads, or density may be tracked over time in a vegetation restoration area. Relevant information can also be gained from targeted research modules[3] (Sections 4-8) designed to examine habitat and space use.
2. Overutilization for commercial, recreational, scientific, or educational purposes. Island foxes are not currently known to be exploited for any of these purposes (USFWS 2004), so monitoring is not applicable to these impacts.
3. Disease or predation. Monitoring to track cause-specific mortality rates, combined with disease surveillance, will provide crucial data concerning primary threats to survival and will provide early warning of new threats.
4. Inadequacy of existing regulatory mechanisms. Lack of prohibitions or enforcement against bringing domestic pets to the islands (e.g., Santa Catalina Island) increases the risk of extinction for island foxes, due to the potential introduction of diseases like canine

[3] Research modules are discrete research projects designed to answer specific questions such as those related to fox biology, ecology, or monitoring methods. Although not intended to be part of long-term monitoring, research modules can inform adaptive refinements to monitoring protocols.

distemper (Timm et al. 2002). Inadequate enforcement of speed limits may also increase the risk of vehicular trauma. Monitoring for survival, including disease surveillance, will increase our understanding of these risks. In addition, research modules (Sections 4-8) can be designed to examine public awareness, traffic patterns, and rodenticide use.

5. Other natural or man-made factors affecting continued existence of foxes. These factors may include competition with feral cats (Phillips et al. 2007), mortalities due to vehicular traffic, lack of genetic variability, and stochastic environmental and demographic factors. Monitoring population size, trends, mortality rates and causes, and densities in specific habitat or geographic areas will provide information concerning these potential impacts. However, the most effective way to increase current knowledge about these factors may be to augment monitoring with targeted research projects designed to complement and make use of long-term monitoring data. Specific recommendations regarding research modules for examining factors or ecological processes affecting island fox populations are presented in Sections 4-8.

2.2 General Population Sampling Considerations

This section summarizes relevant characteristics of island fox ecology as well as important logistical constraints and other considerations that have guided development of monitoring protocols. These foundations were derived initially from studies and discussions related to development of monitoring protocols for foxes on San Clemente Island, guided by workshop discussions with island fox biologists, statisticians, and population modelers (Spencer et al. 2006), and supplemented by input from managers of the other five islands, analysis of current protocols used on each island, and statistical consultation on use of capture data.

2.2.1 Key Biological Issues

The biology of island foxes offers some unique challenges and opportunities for design of a monitoring program, including the following key considerations:

1. Island foxes occupy relatively stable, year-round territories, generally as socially monogamous male-female pairs (Crooks and Van Vuren 1996, Roemer et al. 2001a). At least when populations are high, fox territories appear to nearly fill all available habitat ("territory packing"), although this has not been fully quantified across all habitat types or islands. Home range and territory sizes can vary across habitat type and season and are influenced by population density. In one study on Santa Cruz Island, home range sizes varied between 0.15 and 0.87 km^2, with a mean annual home range of 0.55 km^2 prior to population declines in the mid-1990s (n = 14 foxes, Roemer et al. 2001a), while in another study, home range sizes on San Clemente Island averaged 0.77 km^2 (n = 11 foxes, Thompson et al. 1998).

2. Island foxes inhabit essentially all available vegetation communities on the islands. Although territory sizes and population densities may vary with habitat characteristics, habitat-specific patterns are not well understood (Roemer et al. 2004). For example, on San Clemente Island, fox densities appear to be higher in maritime desert scrub than in annual grasslands, although this relationship could be confounded by other habitat

variables, and some vegetation associations have not been adequately sampled (Spencer et al. 2006).

3. Most young are born from late April through May with a parturition peak in about early May (Laughrin 1971); however, parturition has been documented as early as February on San Clemente Island (Schmidt et al. 2001). Juveniles remain with their parents throughout the summer (until about August or September, Laughrin 1973), and most dispersal from natal areas apparently occurs in late fall or early winter (Timm et al. 2002), although some dispersal may occur later (Roemer 1999).
4. Island foxes are dietary generalists, opportunistically eating a wide variety of plant and animal foods according to their availability, which presumably allows them to persist during periods of varying composition of available foods (e.g., due to fluctuations in vertebrate prey numbers or in seasonal availability of plant foods; Crooks and Van Vuren 1995, Roemer et al. 2004).
5. Island foxes may lack resistance to some strains of disease found on the mainland, probably due to their geographic isolation from mainland populations. Island fox populations are therefore potentially susceptible to dramatic die-offs from exposure to diseases such as rabies or certain strains of canine distemper. For example, the population on Santa Catalina Island declined by over 90% during 1999-2000 due to disease most likely introduced by domestic dogs (Timm et al. 2000).
6. Because they evolved without predators, island foxes do not fear introduced predators, humans, cars, or other potential threats. This behavioral characteristic makes them highly susceptible to vehicular trauma and to predation by golden eagles.
7. Island foxes are relatively easy to capture in live traps, and some individuals may exhibit "trap-happy" behavior (increasing capture probability after an initial capture). Trap-happy behavior may cause overestimation of true density, as mean maximum distance moved may be underestimated as a result of foxes repeatedly entering a single trap or traps in close proximity (Garcelon and Schmidt 2005), or, if unaccounted for, it may cause an underestimate of true density by inflating the estimated capture probability. However, Kovach and Dow (1981) noted that yearlings appear to be more wary of traps than adults are, and may therefore be less likely to be trapped, causing potential bias in observed age structure.

2.2.2 Additional Constraints and Considerations

Several factors influence the feasibility and cost of implementing alternative monitoring approaches on each of the five islands. The following are important considerations in designing a realistic and effective monitoring program:

1. <u>Access</u>
   - Each of the islands has areas of limited access, which restrict field work options. These constraints are discussed separately for individual islands in Sections 4-8.

2. Timing
   - Trapping of island foxes should ideally be conducted in July. Trapping can also be conducted in late June, but trapping earlier than mid-June risks separating dependent young from lactating mothers. Trapping in July may allow an assessment of the percentage of lactating females, while trapping later than July will preclude collection of this information. Pups are also captured during summer trapping.
   - Trapping should be conducted simultaneously on all islands and on different parts of the same island, or at least as close together in time as possible, to ensure sampling during comparable life-history periods and weather conditions. Timing should be consistent across years to facilitate yearly comparisons of population parameters.
   - Disease testing results (to determine disease titers) among pups must be interpreted with caution if collected before July-August, as pups younger than 4-5 months may have antibodies obtained from mother's milk (D. Clifford, UC Davis, pers. comm.).
3. Weather
   - Periods of inclement weather may make roads impassible (rainy season) or fox trapping unwise (cold/wet or hot weather can stress trapped island foxes). Access to traps, once set, must be assured, to avoid leaving foxes in traps for long periods.
   - Climate and seasonal timing of trapping also influence trapping protocols, which in turn affect how data are analyzed. For example, high temperatures may necessitate closing traps during daylight hours. This influences capture probabilities and should be accounted for in density estimation.
4. Animal welfare
   - Given that foxes may exhibit trap-happy behavior, it is important to consider the number of times an individual is captured within a given time period, because frequently captured foxes tend to lose weight during trapping sessions (G. Roemer, New Mexico State University, pers. comm.). Therefore, overly intensive sampling may have negative impacts on the animals.
   - Once traps are set, access to them must be absolutely assured to avoid harming island foxes by leaving them in traps for prolonged periods.
5. Cost-efficiency
   - Given how risk-prone foxes are, managers must maintain a pulse on the populations so that problems are detected in time to avert problems. Monitoring, therefore, must be informative and affordable, so that it can be sustained over the long term. We sought to identify protocols that would provide the best information return on the monitoring investment, so that these long term monitoring programs will see the foxes to and beyond recovery.
   - Island managers must work collaboratively to explore and identify ways of saving resources. For example, activities such as monitoring flights, veterinary activities, or bulk purchase of radiocollars could be coordinated or shared across islands, so that resources (funding, field personnel, and equipment) are used in the most cost-effective manner.

2.3 Overview of Potential Sampling Methods

Spencer et al. (2006) reviewed alternative field methods for monitoring abundance of island foxes, with a focus on methods that provide robust and useful data and that are logistically and economically feasible in light of rugged terrain, limited road access, and potential access limitations. Their review covered techniques that have previously been used for island fox monitoring (e.g., capture-recapture grids, radio telemetry), as well as other techniques that could potentially replace or supplement existing methods (e.g., genetic sampling, track stations, hair snares). Capture-recapture, radio telemetry, and camera stations were identified as primary candidates for monitoring island foxes on San Clemente Island, and we adopted these as candidates for consideration on the remaining islands. Additional methods, such as the use of global positioning system (GPS) collars and molecular genetic techniques, may prove useful in the future as more information is obtained and technology is improved and refined.

2.3.1 Capture-Recapture Trapping

Live-trapping provides detailed data on individuals and, if conducted systematically, important population-level measures as well. Handling animals allows collection of data not effectively collected by other means, such as details about the reproductive status, health, or genetic relationships of individuals. The ability to mark and identify individuals within a population through time allows collection of data on density, survival, dispersal, and home range size. Participants in the January 2006 San Clemente Island workshop were unanimous in recommending continued use of capture-recapture trapping techniques; however, given economic and logistical constraints, there are inherent trade-offs involved in allocating sampling efforts across space and time.

For example, given a finite number of traps that can be set and checked per night, one can envision sampling the area with numerous, small sampling arrays (e.g., points, grids, or transects) or with a few, large sampling arrays. The former (many small) may better sample the full range of environmental variability (and perhaps density) across the region of interest, but with less precision in density estimates at each sample location. The latter (few large) may better estimate local densities, but with less coverage of environmental variability and perhaps population densities.

Density estimation using traditional mark-recapture methods is complicated by the need to estimate the area actually sampled by the trapping unit (the effective trap area), which requires adding a buffer strip around the outermost traps to account for foxes living outside the unit that may encounter traps. This buffer is generally estimated based on the maximum movements of trapped animals, either as half or full mean maximum distance moved (MMDM), or based on other estimates of movement, but the theoretical basis for most approaches is tenuous (Parmenter et al. 2003). Buffer estimates are often biased and contain considerable uncertainty, which influences the accuracy and precision of density estimates (Wilson and Anderson 1985). The uncertainty of buffer estimates is magnified with elongated trap configurations with high edge-to-interior ratios. When using transects (a configuration that is most feasible on the rugged larger islands), the entire trapped area is defined by this uncertain buffer and, thus, traditional mark-recapture statistics are generally unable to yield valid density estimates (Section 2.4).

Spatially explicit mark-recapture analysis approaches, such as implemented in program DENSITY (Efford 2004, Efford et al. 2004, Borchers and Efford, In Revision), offer a solution to this complication (Section 2.4.1).

Sampling is by nature spatially restricted, but it is often desirable to extrapolate local density estimates to the entire area of interest, such as for island-wide population estimates. However, such extrapolation requires that densities measured at sample locations represent densities over the entire area of interest using design-based or model based inference. Design-based approaches use randomization of sampling locations to ensure valid extrapolation, while model-based approaches link site attributes to density measures and extrapolate population estimates based on the prevalence of these site attributes across the area of interest. Stratification is one option which may improve overall precision, regardless of the approach to extrapolation. Stratification by habitat (collecting data from particular habitat types) is also an essential part of model-based approaches to population estimation.

Some spatial variation in true local densities of foxes undoubtedly exists both among and within habitat types due to the influences of habitat on demography and to demographic stochasticity and historical effects (e.g., uneven impact of past disease or proximity to eagle nests). For this reason, a statistically rigorous sampling design (random, stratified random, or systematic with random origin) is desirable.

Trapping regimes must consider trap-happy behavior, in which capture probability increases after initial capture (Kovach and Dow 1981, 1986), as this may reduce mean maximum distance moved and thus cause overestimation of true density (Garcelon and Schmidt 2005). Timing of trapping also deserves careful consideration, because age, sex, and reproductive status can influence the probability of capture and distances moved, thereby possibly influencing density estimates, as well as estimates of population sex ratio or age-structure (Kovach and Dow 1981).

2.3.2 Radio Telemetry

Tracking individual animals over time (e.g., with radio telemetry) can yield information such as space use patterns (home range, territoriality, dispersal, etc.), temporal activity patterns, habitat preferences, and survival.

Tracking territory size has been suggested as one approach for estimating population density and abundance, assuming that territories are packed such that density is inversely proportional to territory size. This approach may be problematic, however, because it assumes that density (of families or pairs) is equal to the inverse of territory size, that family group size is constant, and that all animals are in family groups or pairs. It also requires that many individuals are radiocollared and that adequate locational data are obtained.

Previous studies used telemetry data to generate home range sizes that were then used to generate density estimates for comparison with capture-recapture estimates (e.g., Schmidt et al. 2002). However, in some cases animals were tracked for only part of a year, thereby failing to represent seasonal variation in habitat use, and animals on different grids were tracked during different seasons, possibly biasing inter-grid comparisons of home range size and population density (Schmidt et al. 2005). This approach could be improved if animals were tracked for longer time periods, if temporal sampling represented the entire study period, and if these factors remained similar among all animals and locations. Moreover, if telemetry data are used to calibrate population densities or other parameters measured on capture-recapture grids, these different sampling methods must overlap in time, to ensure they are both sampling the same population of individuals. It is unclear from some previous studies whether this was the case.

A few studies (e.g., Fuller et al. 2001) have estimated densities of other carnivore species by mapping territories of radiocollared individuals. Fuller et al. (2001) found that territory mapping provided results similar to camera mark-recapture estimates of fisher density. However, this technique requires that a high proportion of animals be radiocollared to detect density changes over time; for example, Fuller et al. (2001) collared over 50% of the fisher population to detect a 20% change in density.

An additional potential approach for estimating density with the use of radio-collared animals is to combine telemetry data with trapping data. This approach calls for delineating the area (A) associated with a trapping unit, and then determining the proportion of locations within the trapping unit for radio-collared animals. A density estimate for each unit is based on the ratio of the proportion of locations within the trapping unit to probability of capture (G. White, Colorado State University, pers. comm., Appendix O), divided by A. This method would require 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.

The greatest value of radio telemetry for addressing objectives identified in this report will be to monitor survival and cause-specific mortality rates (Section 2.4.2). Mortality signals (indicating that the animal has stopped moving for a pre-determined time) should be monitored such that possible mortalities can be investigated promptly and cause of death determined. Signals can be monitored from the ground, from the air (via plane or helicopter), or remotely via receivers placed on towers. Because topography (hills, mountains, and steep canyons) can interfere with signal acquisition, checking signals can require great effort, especially on the three large islands. Remote towers, which obtain signals and relay them to the researcher, offer an alternative, but multiple towers are needed to access locations from all parts of the island. Aerial telemetry checks provide the most efficient means of checking signals but, like telemetry towers, they have a large monetary cost.

In addition to survival monitoring, habitat use and habitat selection studies can benefit from the use of radio telemetry (see recommended research modules in Sections 4-8).

2.3.3 Camera Stations

Remotely located cameras using motion-sensing triggers may be a useful supplement to trapping and telemetry methods, although further investigation and pilot studies are necessary to refine methods and decide if cameras will provide useful data at reasonable cost. Cameras can be used to investigate distribution and habitat selection by providing presence data for occupancy models (MacKenzie and Nichols 2004). Marking foxes for individual identification in photographs (e.g., using one or more combinations of ear tags, collars, or fur dyes) or the use of pit-tag readers could facilitate the use of camera stations as a non-invasive means of estimating island fox density and abundance via mark-recapture methods. Cameras may be feasible for density estimation in areas where trapping is not feasible due to limited access (e.g., in areas where occasional access for servicing camera stations is more feasible than the prolonged access necessary for trapping studies).

Placement of cameras is important for density estimation, such that all animals in the study area, whether marked or not marked, have an equal probability of being photographed. Because island foxes are reliably territorial, many stations would be required, because each station is likely to repeatedly photograph territory residents but not other foxes, or extensive movement of camera stations would be required. Observability (i.e., photo "capture" rates) may also vary with differences in vegetation structure or topography, introducing heterogeneity that must be accounted for to avoid additional bias in density estimates by habitat type. Because foxes can be trapped with relative ease and high safety, allowing physical assessment, health sampling, and individual marking, camera traps offer fewer advantages for foxes relative to more cryptic, wide-ranging, and hard to trap species for which this method is frequently employed.

Previous studies have placed cameras along travel routes (e.g., trails) to increase detection probabilities. However, this may bias spatial representation, unless locations are carefully stratified across habitat types (Wilson and Delahay 2001). Studies of other species have used bait to lure animals to camera stations to increase "capture" success, but baiting of camera stations, as well as trapping sites, can introduce space-use biases by drawing individuals to locations (or habitats) they normally don't use (W. Spencer, CBI, pers. comm.). The decision to bait therefore depends on the objectives and assumptions of the study.

In conclusion, although camera stations hold promise as a future research or monitoring tool for island foxes, we suggest that pilot studies first be conducted to determine whether they would provide useful data at reasonable cost to supplement or replace trapping and telemetry studies. Such studies should also examine the potential of "hybrid" methods that combine cameras with the design and analytical approaches typically used in mark-recapture studies. In addition, the potential for camera data to serve as an index to population trends should be examined. Currently, camera stations may be useful for addressing specific, focused research questions (Sections 4-8), rather than for long-term monitoring of island fox populations.

2.3.4 GPS Technology

GPS technology offers an attractive alternative, or possibly addition, to telemetry tracking, because it allows remote recording of the animal's location, rather than active recording by field workers. GPS tracking can thus be much less labor-intensive than radio telemetry. In addition, animal locations can be obtained at night and in inaccessible areas, such as steep rugged areas or areas far from road and trail access. However, some precautions must be taken in the use of GPS collars. There may be biases in areas of dense vegetation or rugged terrain, because closed canopies or other physical features may reduce the ability of GPS collars to obtain locations (e.g., Dussault et al. 1999). This would require careful consideration or modified data analysis in studies of habitat use by island foxes. In addition, the high cost of GPS collars will reduce the number of animals that can be tracked, which can have implications on statistical analyses and power. For example, due to the current high cost of each GPS collar, there may be a tendency for studies to produce large amounts of locational data on few animals versus a moderate number of locations on a larger sample of animals. This may be appropriate, however, depending on the objectives of the study.

Until recently, the weight of GPS collars was deemed too great to be safely applied to island foxes. However, technological improvements have reduced the weight of collars to an acceptable weight, and a pilot study has been initiated to explore the use of GPS collars on several of the islands (B. Cypher, California State University, Stanislaus, pers. comm.). Until their cost is reduced, it is unlikely that GPS collars will be able to replace traditional VHF collars for tracking island fox survival due to the large numbers of animals that need to be tracked (Section 2.4.2). However, the use of GPS collars should be explored as a potentially cost-effective approach for monitoring survival on the three large islands, where large investments in aerial monitoring would otherwise likely be needed (Section 2.4.2). In addition, GPS collars may provide a valuable tool for studying space use and habitat selection, as well as calibrating the degree of bias of different sampling methods. For example, GPS collars could be used to examine potential biases that may result from trapping foxes along road or trail networks.

2.3.5 Genetic Analyses

Genetic techniques can provide data not readily available from direct observation or handling of animals, such as kinship among individuals or genetic profile of a population. DNA may be obtained from tissue samples while handling trapped animals, or from scat or hair without the animal being trapped or handled. Remote collection of samples (scat, hair) has gained popularity as a noninvasive means of monitoring wildlife, especially for monitoring elusive carnivores. If an adequate number of samples is collected, the maximum number of unique genotypes may be used as a minimum population size. Alternatively, mark-recapture techniques may be used, with repeat collection of the same genotype viewed as a “recapture” (Wilson and Delahay 2001).

Genetic methods can be noninvasive (if samples are collected remotely), they may be used to generate absolute abundance estimates, they allow the researcher to determine the identity and sex of the animal, and they allow passive sampling in areas of low accessibility where trapping may not be feasible. They therefore provide an alternate means of estimating measures such as effective population size, home range size, and dispersal. However, population estimates based on genotypes may be biased high by genotyping errors (Waits and Leburg 2000, Harrison et al. 2002). Pilot studies would be necessary to determine genotyping error rates and to provide an estimate of expected confidence intervals (Wilson and Delahay 2001). Genetic analyses may be costly (Harrison et al. 2002), and some data currently obtained via trapping, such as health status and age, are not obtainable through genetic analysis. Finally, because the number of loci or microsatellite profiles necessary to positively identify individuals increases with decreasing genetic variation in the population (Wilson and Delahay 2001), and because island foxes have low genetic variation (Wayne 1996), identification of individual foxes via genetic techniques may be more difficult than for other species.

As current objectives require a large number of island foxes to be captured and handled each year, to apply radio collars and for vaccination, it is unlikely that genetic methods alone could address current monitoring objectives. However, genetic methods may be used to augment currently proposed methods, for example, as a means of monitoring fox densities in areas of low accessibility (e.g., the north shore of Santa Cruz Island), or as part of focused research modules to study reproduction (Sections 4-8). Current research is examining methods of estimating population size by genotyping island fox fecal samples (M. Gray, UC Los Angeles, pers. comm.); therefore, "hybrid" methods that combine genetic sampling with the design and analysis typically used in mark-recapture studies should be explored as a future method of estimating population size.

2.4 Development of Island-Specific Trapping and Survival Monitoring Protocols

In this section we present our general approach for identifying the recommended trapping and survival monitoring protocols for each island to address the objectives outlined in Section 1.2. Specific analyses and recommendations for each island are discussed in Sections 4-8. In developing these protocols we attempted to satisfy multiple monitoring objectives in the most efficient and cost-effective manner. For example, generating population estimates and monitoring survival in a subset of collared animals both require trapping efforts. To minimize stress to foxes, as well as labor and equipment costs, we recommend scenarios in which both these objectives may, for the most part, be met with one annual trapping effort, thereby making the best use of valuable personnel resources and reducing disruption to foxes that might occur from multiple trapping efforts.

2.4.1 Island-Specific Trapping Protocols

Goals

Our goal was to identify appropriate trapping protocols for each island and provide data to estimate the following parameters relative to trapping goals (Section 2.1):

1. Parameters for tracking population recovery
   - Annual population size estimate, presented with an 80% confidence interval.
   - Estimate of trend in population size, generated from annual abundance estimates or population models. This estimate has no targeted precision; rather the precision of the trend estimate will be determined by the precision of population estimates
2. Parameters for island-specific management decisions
   - Habitat- or vegetation-specific density on San Nicolas, Santa Catalina, Santa Rosa, and Santa Cruz.
   - Indices of reproduction on San Miguel and Santa Rosa.

3. Threat-based monitoring
   - Demographic data such as abundance, trends, age structure, and health to identify and address threats.

Strategies

We designed protocols intended to be feasible and to generate robust estimates of population size. Although one standardized sampling approach across all islands is desirable, objectives and constraints differ somewhat across islands (Section 2.2.2 and Sections 4-8), and island-specific protocols must be tailored accordingly. The key parameters obtained from trapping should nevertheless be comparable among islands. For example, population estimates for each island should be generated via statistically robust methods, even if the actual trapping protocols used to obtain field data vary among islands.

We considered several trapping approaches and configurations expected to provide good parameter estimation for population size and trend (Box 2-2). Spencer et al. (2006) explored systematic island-wide trapping in developing monitoring protocols for San Clemente Island. Although this method could likely provide a robust population estimate, Spencer et al. (2006) concluded that the large number of traps required was impractical, and we therefore did not consider this option further in our analyses. Although experts at the January 2006 San Clemente Island workshop recommended that capture-recapture trapping techniques using traditional grid trapping could provide robust and cost-efficient demographic data, the use of large trapping grids is not feasible or safe on Santa Catalina, Santa Rosa, and Santa Cruz islands due to rugged and steep terrain. Transect trapping protocols currently used on Santa Catalina and Santa Cruz are problematic, however, due to (a) difficulty in estimating the effective trap area around transects, (b) potential bias of transects set primarily along roads, and (c) the extremely labor and time-intensive nature of the transect system, which resembles a census rather than a sampling regime (also see Sections 6.3.3 and 8.3.3). Santa Rosa Island does not yet have any standardized trapping protocol.

We solicited advice from two outside statisticians─E. Rexstad, University of St. Andrews, Scotland and J.A. Royle, USGS Patuxent Wildlife Research Center─on additional alternatives for estimating density, in particular on the three large islands where grid trapping would not be possible. They suggested the following two options:

1. Mark-recapture sampling using the island as the effective trap area, with random trap locations.
   This recommendation, which was viewed as statistically robust by all three statisticians, was to use traditional mark-recapture methods using the entire island as the effective trap area rather than delineating separate sampling areas. The fact that we are attempting to estimate population size (N) within a closed system (an island) eliminates the need to estimate the effective trap area (A), which makes this a statistically appealing approach. To satisfy assumptions of mark-recapture methods, however, all foxes on the island have to have equal probability of being trapped (Seber 1982). This method requires, therefore, that traps be placed randomly or systematically on the island, and then moved randomly as individual traps or as a randomly shifted grid, respectively, before each subsequent

trapping occasion (e.g., night) during each trapping session. Determining the number of traps and nights required to obtain an adequate number of recaptures and the targeted precision in the estimate of N would require additional evaluation. This method, hereafter referred to as island-wide random trapping, differs from island-wide systematic trapping in that it requires fewer traps (Box 2-2).

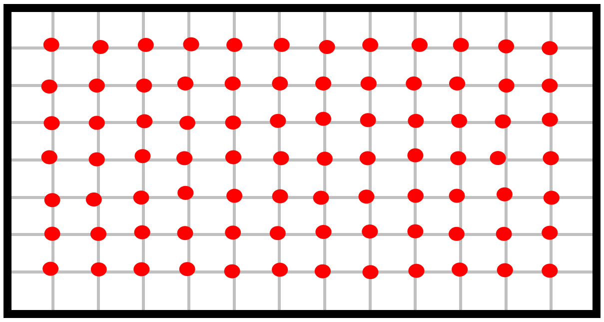
2. Transect sampling, analyzed using spatially explicit capture-recapture methods. The primary limitation of transect trapping is the challenge of estimating the effective trapping area (A) around the transect. Rigorous methods for estimating A have not been developed for transects (Efford 2004), but an estimate of A is necessary to use transect data in combination with traditional mark-recapture estimation (which provides an estimate of N) to estimate density following the equation $[\hat{D}] = [\hat{N}]/A$. To date, transect data collected on Santa Catalina and Santa Cruz were converted to a density estimate by assuming a 500-meter radius effective trap area, based on approximate home range size for foxes on San Clemente Island and translocated foxes on Santa Catalina Island, and using this area as an estimate of A (Schmidt et al. 2004). This distance could, however, be influenced by habitat type and density of the fox population (due to changes in home range size), thereby altering true A and D. Therefore, use of a standard distance to estimate A results in estimates of D that are biased to an unknown degree.

   The recently-developed program DENSITY offers one solution to this complication (Efford 2004, Efford et al. 2004). This program bypasses the need to estimate N or A, and estimates D directly by (a) simulation and inverse prediction or (b) maximum likelihood estimation. These methods fit a two-parameter spatial detection function that describes movement patterns and capture probabilities when encountering a trap (Efford 2004, Efford et al. 2004). Maximum likelihood estimation allows more flexibility in terms of inclusion of covariates and model selection than does inverse prediction (Borchers and Efford, In Revision). In our analyses, we use program DENSITY to evaluate the use of multiple small trapping units (Box 2-2). Although our goal was to evaluate and maximize the precision of the population estimate, $\hat{N}$, we were able to focus our analyses on the precision of the density estimate, $\hat{D}$, because the two parameters are related through the equation $\hat{D} = \hat{N}/A$, so that the relative precision of $\hat{N}$ is numerically equal to the relative precision of $\hat{D}$.

As we had a limited number of trapping options that would enable good parameter estimation (Box 2-2), we evaluated methods judged to be feasible by determining the effort required to obtain the targeted precision of N (i.e., CV[$\hat{N}$] ≤20%; Section 2.1.1). We first evaluated the feasibility of island-wide random trapping, due to the statistical robustness of this method. This approach was explored for the two smaller islands, San Miguel and San Nicolas islands, and for Santa Cruz Island as a trial for the larger islands. Using program DENSITY to simulate realistic fox behaviors (movement patterns and capture probabilities), we determined the trap spacing and numbers of trap-nights required to obtain the targeted precision of $\hat{N}$, considering the size of each island. Simulations used several plausible population densities and behavioral parameters (Sections 4-8, Appendices K, L, and M).

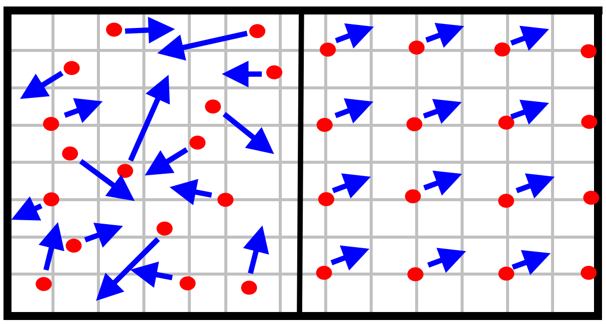
Box 2-2. Trapping Configurations Considered.

Given that trapping has been chosen as an efficient tool for monitoring island foxes, there are limited options for trapping configurations that will achieve the goals of generating statistically robust estimates of population size ($\hat{N}$) and trend. Here we present the limited options schematically on a hypothetical rectangular island:



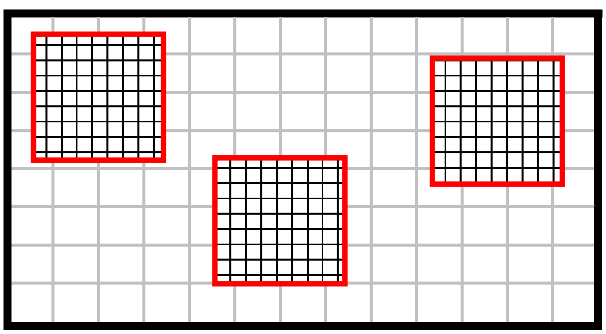
Island-wide Systematic Trapping

Traps are placed systematically (and remain in same location during entire session). Traps must be < 600 m apart to allow for equal opportunity of capture for all foxes. $\hat{N}$ is estimated via mark-recapture methods. Island is considered the effective trap area.



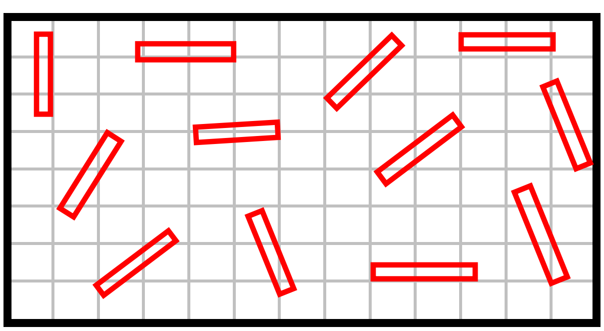
Island-wide Random Trapping

Traps are placed randomly (left side of schematic) or systematically (≤ 1200 m spacing; right side of schematic), and are moved to new random locations individually or randomly as a shifted grid (up to ½ inter-trap distance), respectively, before each trapping occasion. $\hat{N}$ is estimated via mark-recapture methods. Island is the effective trap area.



Traditional Trapping Grids

$\hat{N}$ is extrapolated from local grid densities, based on (a) mark-recapture estimates of local abundance in combination with estimated local effective trap area (from distances moved by recaptured animals) or (b) spatially explicit capture-recapture methods using movement and detection patterns alone (Efford 2004, Borchers and Efford, In Revision).



Multiple Small Trapping “Units”

$\hat{N}$ is extrapolated from local unit density via spatially explicit capture-recapture methods (Efford 2004, Borchers and Efford, In Revision). Traditional mark-recapture methods cannot yield precise density estimates for transect-shaped units due to edge effects.

For San Miguel and San Nicolas islands, we also evaluated precision resulting from existing protocols (existing grids and number of nights trapped) and variations of these protocols involving different numbers and sizes of grids as well as different numbers of nights. Given a certain trap layout and duration, resulting precision depends largely on the number of recaptures. Recaptures, in turn, are determined by the density of foxes and their behaviors that influence detection by the sampling system. Program DENSITY models these behaviors using the two detection parameters described above (Efford 2004, Efford et al. 2004, Appendix K and L). Simulations were run with a range of plausible densities and detection parameters. In addition, V. Bakker generated a best estimate of detection parameters, using actual trap data from multiple years and multiple islands with program DENSITY. Data archives from the many years of field work on the various islands provide a valuable resource for identifying these best estimates. Results of these simulations were compared to determine precision resulting from different levels of effort (Sections 4 and 5, Appendices K and L).

For the three larger islands, we explored the use of multiple trapping units, which would be smaller than typical grids (thereby more logistically feasible on the three large islands), but which could be evaluated in a robust manner using program DENSITY. Simulations for the large islands were also conducted using a plausible range of population density and detection parameters, as well as a best estimate for the detection parameters, to compare precision resulting from different levels of effort (Sections 6-8, Appendix M). For the larger islands we attempted to modify existing approaches of island-wide transect trapping so that monitoring would retain the feasibility of current systems but yield robust density estimates.

For each island, we examined the various trapping scenarios in terms of expected precision, required field effort, and likely representation of habitat variability on the island. To account for spatial heterogeneity in local densities (Section 2.3.1), we focused on protocols that use statistically rigorous sampling design, with trap layout determined by random, stratified, or systematic with random origin placement. Confidence intervals around estimates of island wide abundance should be calculated to include spatial variance (Skalski 1994). For San Nicolas and San Miguel islands, we chose random placement of trapping layouts, due to the small size of these islands and their relatively homogeneous habitat. For the three larger islands, we considered stratification by vegetation and other habitat characteristics; however, the interspersion of habitat types as well as temporal changes in vegetation make this approach impractical. In addition, the rugged terrain on these islands precludes trapping in areas not accessible by roads. We therefore randomly sampled a subset of the island, with locations selected to begin at random locations on the road network, and actual direction of trap units (from the road) determined randomly. For logistic and safety reasons, trap units were shifted, when necessary, so that actual trap locations avoided the steepest terrain (>30% slope). Although the effective trap area could include these steep areas, sampling was likely biased towards gentle terrain, and undoubtedly biased to areas in proximity of roads. However, this approach essentially samples areas representing 99-100%, 96-99%, and 85-88% of Santa Catalina, Santa Rosa, and Santa Cruz islands, respectively, if effective trap radii range from 300 to 600 meters. We assume that Santa Catalina and Santa Rosa islands are essentially sampled completely by this approach, and we suggest that future research examine whether the 12-15% of Santa Cruz Island not sampled by this protocol differs from sampled areas in terms of fox density.

Recognizing trade-offs between effort (and what is logistically feasible) and the desire to increase precision and habitat representation on each island, we selected the most promising two to three scenarios for each island, analyzed habitat representation on two scenarios for each island, and present them as recommended scenarios in the island-specific sections of this report (Sections 4-8). The choice of which scenario or variation of a particular scenario to use must, however, ultimately be made by each island manager, based on a balance between feasibility and desired precision. The scenarios suggested for each island provide examples of effort and expected precision, with the latter expected to change with changes in fox density, even when protocols (and effort) remain the same. The effort required for a particular protocol will also vary with changing densities because the number of foxes caught in a particular trapping protocol will change as density varies, thereby changing the amount of time required to check and service traps.

Changing population status may allow managers to reduce trapping effort. First, because precision scales with population size, precision goals may be reached with reduced effort at larger population sizes. Additionally, managers may desire to reduce precision targets as population status improves, such as when a population is large and has high survival (i.e., it has low risk of quasi-extinction, Section 2.1.1). In these cases, reduced trapping may be desirable because of reduced cost and reduced risk of stress and disruption to foxes. In the case of multiple small trapping "units," this may be accomplished by reducing the number of units trapped on the island. It is important that the reduction of number of units uses a random approach. That is, if reducing the number of units from 24 to 18 units, the six units to be removed should be chosen randomly, even if there is a temptation to remove units that have had low trap success (the proportion of captures per trap-night) or those that are more difficult to trap. Trap effort can, alternatively, be reduced by maintaining the same number of units and reducing the number of nights trapped. In addition to loss of precision, these decisions should consider labor and time saved by each option and the loss of habitat representation that will occur if units are removed from the protocol.

For analysis of resulting data, we recommend that density estimates be made using maximum likelihood spatially explicit capture re-capture methods implemented in program DENSITY, or, if grid size allows, closed population mark-recapture models implemented in program MARK (White and Burnham 1999). In either case, information theory should guide model selection (Burnham and Anderson 2002).

2.4.2 Island-Specific Survival Monitoring Protocols

Despite captive breeding programs, eagle removal, and other habitat management strategies, island foxes remain at high risk and will remain at risk even after recovery. Being an island species, they are especially vulnerable to invasions by nonnative predators (e.g., golden eagles) and disease (e.g., distemper), as demonstrated by the near loss of subspecies on the northern islands (due to eagle predation) and on Santa Catalina Island (apparently due to disease). Other causes of mortality such as vehicular trauma are not well estimated, and it is not known how much they influence the viability of island fox populations.

The importance of survival monitoring is well-recognized among island fox managers and biologists. Managers of all five islands identified survival monitoring, along with monitoring to determine cause-specific mortality rates, as a primary monitoring objective, and the Recovery Coordination Group (RCG) identified survival monitoring as a key component of proposed recovery criteria. In this section we discuss our approach for identifying protocols for survival monitoring.

Goals

Previous studies on island foxes have estimated annual survival from annual trapping data or telemetry data. However, no previous studies have been able to provide robust estimates of cause-specific mortality rates, either because the fates of individual animals were not monitored over an adequate time period to estimate this parameter and its variation across years, islands, and age/sex classes, or because monitoring was too infrequent to determine cause of death. As part of an earlier process and San Clemente Island workshop discussions, biologists, managers, and statisticians concluded that survival monitoring and determination of cause-specific mortality rates would require radiocollaring and frequent monitoring of individual foxes, and that this would produce more appropriate and useful information on these parameters than data collected via annual trapping (Spencer et al. 2006). In addition, Spencer et al. (2006) recommend that animals be tracked over long time periods, representing all seasons of the year, to provide a complete picture of mortality patterns.

The risks of eagle predation and disease currently create the primary need for survival monitoring. Because the detection of either eagle predation or disease would trigger management actions (e.g., eagle removal, vaccination, or capturing foxes for quarantine), survival monitoring must be continuous and occur in “real time,” lending further support for the need to track radiocollared animals continuously on each island. The required number of collared animals and the frequency at which they need to be monitored are influenced by several factors, including the purpose of monitoring (for detecting predation versus disease), the ability to respond quickly with management actions, the feasibility of monitoring at various intervals on each island, and survival monitoring needs related to tracking recovery.

In terms of monitoring, there is a need to detect eagle predation in real time to trigger management actions, and there is a need to address one of the proposed recovery criteria for island foxes, namely, to detect an eagle-specific annual mortality rate of 2.5% or greater over a 3-year period. To address the first need, managers must maintain constant vigilance for eagle predation and maintain a population of radiocollared foxes on each island. Simulations by D. Doak (UC Santa Cruz, Appendix N) suggest that an eagle-specific mortality rate of at least 2.5% over a 3-year period can be detected if 40 radiocollared foxes are monitored continuously on each island. The frequency of monitoring (checking collared animals for mortality signals) should be high enough so that cause of mortality can be determined with reasonable confidence. Carcasses must be located promptly so that (a) initial mortality site investigations can be conducted on fresh carcasses (which, in the case of eagle predation, would assist trained field personnel in identifying that cause of death), and (b) fox carcasses are transported to UC Davis rapidly enough for a meaningful necropsy.

A primary goal for disease surveillance is to detect a disease outbreak quickly enough to trigger management actions (e.g., treatment, vaccination, or quarantine) fast enough to be effective. This formed the basis of disease surveillance monitoring recommended for San Clemente Island (Spencer et al. 2006). Recommendations for that island were based on computer simulations by D. Doak, D. Clifford, and V. Bakker which evaluated the number of monitored animals and the frequency of signal checks needed to respond effectively to a disease outbreak, assuming rapid response once a mortality is detected. However, managers, veterinarians, disease ecologists, and biologists have since decided to seek greater protection than could be provided by a disease-response protocol alone (Island Fox Health TEG unpublished report, June 22, 2006). At the RCG meeting in Davis, California, in December 2006, participants decided that maintaining a core group of animals vaccinated against rabies and distemper would provide the most effective and efficient safeguard against a disease outbreak, again based on simulations by D. Doak (UC Santa Cruz, unpublished data), consistent with a strategy recently recommended to protect Ethiopian wolf (*Canis simensis*) populations from rabies outbreaks (Haydon et al. 2006)[4]. However, survival monitoring was still deemed necessary to (a) detect a disease outbreak other than rabies and distemper, (b) allow evaluation of vaccine efficacy in the event that a rabies or distemper outbreak occurred, and (c) monitor other causes of mortality.

The Fox Health TEG provided input on the number of radiocollared animals and the frequency with which they should be monitored for the purpose of disease surveillance. Although computer simulations guided recommendations for disease surveillance on San Clemente Island (Spencer et al. 2006), it was decided that further similar simulations, to incorporate different population sizes on the five remaining islands and the presence of vaccinated animals, was not justified as it would not alter on-the-ground management decisions in the face of a disease outbreak. Rather, it was decided that existing information was sufficient to select a target number of monitored (radiocollared) animals. Specifically, because the recommendation for San Clemente Island disease surveillance was 40-60 radiocollared foxes, and the recommendation for detecting a $\geq$2.5% eagle-specific mortality rate was 40 animals, it was decided that 40 radiocollared animals would be the target number to be monitored on each island. It was recognized that different population sizes, if incorporated into a model similar to that developed for San Clemente Island, would result in different model outcomes; however, the presence of a vaccinated core of animals would likely reduce the recommended number of animals.

Monitoring frequency for the target 40 animals is critical, because these animals will act as sentinels for detecting (a) disease outbreaks other than rabies or distemper (i.e., diseases for which the population is not protected via vaccination), (b) a rabies or distemper outbreak so that unvaccinated animals could be vaccinated and that vaccine efficacy among vaccinated animals could be evaluated, and (c) other causes of mortality such as eagle kills, vehicular trauma, or dog attacks. The key factor in deciding the frequency of signal checks is the ability to find a carcass and transport it to UC Davis, quickly enough to allow for a meaningful necropsy. The Fox Health TEG advised that, ideally, the 40 animals should be checked every 24 hours. An additional day will inherently be added to the time between death and necropsy as it will require at least 1 day to locate and transport the carcass to necropsy. If this goal proves infeasible, signals from the 40 animals should be monitored no less than every 2-3 days in the winter months, and no less than every 1-2 days in the summer, as high temperatures can quickly

[4] The number of vaccinated animals and their geographic distribution will be determined by the Fox Health TEG.

deteriorate the condition of a carcass and compromise the ability to obtain meaningful necropsy results. Although less frequent monitoring (such as once per week) may be adequate for monitoring eagle predation, it would not be ideal (because desiccation and scavenging can reduce accurate determination of cause of death even in the case of predation), and it would not be adequate for disease surveillance.

Strategies

Monitoring at least 40 animals on a frequent schedule can be challenging due to poor accessibility, limited personnel and vehicles, and weather constraints. The following options or combinations of options should be tailored for each island:

- Monitor signals from the ground, traveling by vehicle and by foot.
- Monitor signals from the air, via helicopter or airplane.
- Monitor signals via remote receivers or via GPS collars.

Several strategies were discussed with the Fox Health TEG for maximizing monitoring frequency. First, it may be possible to adjust the number of monitored animals based on feasible monitoring schedules. For example, if it were deemed impractical to monitor 40 foxes every 1-2 days in the summer, but feasible to check signals every 3 days, then the number of collared foxes could be increased to 60-120 foxes, maintaining the same daily target ratio (average number of foxes checked per day). Although the chances of picking up the same number of total dead foxes over a given time period could stay the same, a greater proportion of these carcasses would be "older" carcasses (those dead for a longer period of time), thereby decreasing the chance of a meaningful necropsy. For this reason, this strategy is not preferred.

An alternative strategy is to check foxes on alternate days on a geographic basis. For example, if it is impractical to check 40 foxes distributed across the entire island every 1-2 days, radiocollared animals could be distributed so that 20 foxes on one part of the island were checked one day, and another 20 animals on a different part of the island were checked the next day. The Fox Health TEG stressed, however, that a daily check on all the animals is preferred.

Frequent monitoring of collared animals can be facilitated by using a remote telemetry system that systematically checks signals and records information on signal status (live versus mortality mode). A remote telemetry system currently being developed and tested for San Nicolas Island may provide a useful model [D. Garcelon, Institute for Wildlife Studies (IWS), pers. comm.]. The system on San Nicolas Island records and stores data from signals multiple times per day, thereby allowing logging of information at night when fox radio signals may be detected more readily (if foxes are more active at night). The system being developed for San Nicolas Island has similar limitations as any telemetry system in that signals not in line-of-sight are difficult to detect. Currently telemetry receivers are located on the ground, but elevation of receivers (or at least the receiving antenna) on towers would increase the area monitored by each receiver (D. Garcelon, IWS, pers. comm.). A similar remote monitoring system, with receivers positioned on high towers, has been used successfully at Fort Irwin, California, to track desert tortoises (*Gopherus agassizii*) and was suggested as a monitoring option for San Clemente Island (Spencer et al. 2006). Spencer et al. (2006) described this system and discussed considerations for its implementation. This system allows information on signal status to be transmitted to biologists remotely (either to a centrally located computer or to a remote location via email). The system being developed on San Nicolas Island will likely have this capability in the near future (D. Garcelon, IWS, pers. comm.).

Monitoring of signals from the air (via airplane or helicopter) offers another option for frequent signal checks. This method allows for relatively easy detection of signals in canyons and along rugged shorelines, and can provide approximate locations of mortalities, thereby making carcass recovery more efficient. However, aerial monitoring is costly and can be disrupted by weather or mechanical problems. As aerial monitoring may be an important monitoring option for the three largest islands (Santa Catalina, Santa Rosa, and Santa Cruz), island managers [Santa Catalina Island Conservancy (SCIC), NPS, and TNC] should explore the economy of scale of jointly contracting a pilot and airplane to monitor the three islands on a regular basis. This should reduce the collective cost of monitoring foxes on these large islands. Signal checks on 120 foxes across three islands could likely be accomplished in a fixed-wing flight from the mainland in less than 4 hours [T. Evans (pilot), CDFG, pers. comm.]. As this would largely replace intensive long-term ground monitoring, and associated personnel and vehicle costs, this may be a cost-efficient monitoring approach. In the event that weather or mechanical problems temporarily interfere with aerial monitoring, it would be necessary to have field crews mobilized to check signals from the ground. In addition, at least one person would have to be available on each island to immediately locate and collect carcasses in the event that a mortality is detected.

The use of GPS collars should also be explored as a means of survival monitoring. Although the cost of purchasing a large number of GPS collars may be prohibitive, the cost of this option should be evaluated and compared to the cost of tracking 40 animals wearing VHF collars. If satellite GPS collars (collars that can upload data via satellites as opposed to “store-on-board” GPS collars) could be used on island foxes, this may be a cost-efficient option on the three large islands in particular, where large investments in aerial monitoring or extensive labor costs for ground monitoring would otherwise be necessary. Furthermore, bulk purchases of collars for multiple islands may reduce the unit price. We suggest that island managers work collaboratively to evaluate and compare the cost-effectiveness of all the above methods of monitoring collared animals (ground monitoring, remote telemetry monitoring, aerial monitoring, and GPS monitoring) as an aide in choosing the appropriate long-term monitoring approach for each island.

The choice of which 40 animals to collar is also an important decision, and we suggest the following guidelines:

1. Collared animals should be distributed across each island, rather than being clumped in one area, to best sample survival that may vary geographically and to detect disease outbreaks prior to spread.
2. Collared animals should represent all age classes. Currently, the Fox Health TEG recommends that 20 1-year-old animals be collared each year for survival monitoring. We suggest that these 20 young animals be included in the recommended 40 animals, and that the remaining 20 animals represent older age classes in the population.
3. Collared animals should include equal numbers of males and females.

4. As suggested by the Fox Health TEG, animals monitored for survival should not be vaccinated against disease, as they should represent true sentinels for disease. Although the ideal scenario would be to monitor an equal number of vaccinated and unvaccinated animals for survival and cause-specific mortality, thereby facilitating a vaccine efficacy study in the wild and allowing the use of vaccination status as a covariate in a hazard analysis, the challenge of intensely monitoring adequate numbers of animals on each island led us to recommend maximizing the number of true sentinels for disease (i.e., unvaccinated animals that are tracked) at the expense of monitoring vaccinated animals. Annual trapping data may be analyzed to assess survival rates relative to vaccination status. We agree, however, that vaccine efficacy studies should be conducted in the wild population or in a captive setting in the future, as opportunities arise. On islands with very small populations, it may be difficult to maintain both the targeted number of unvaccinated radiocollared animals along with the required number of vaccinated animals. In this case, adequate animals should be vaccinated, as per Fox Health TEG recommendations, even if it means that radiocollared animals are vaccinated. As the population grows, unvaccinated animals should be collared for survival monitoring.

Ideally, a new set of 40 collars should be applied every year during annual census trapping. Annual selection of 40 animals for survival monitoring will also satisfy the Fox Health TEG's recommendation that 20 1-year-old animals are collared each year. Rather than collaring the first 40 animals trapped, animals to be collared should be selected by a predetermined set of criteria[1] to represent the appropriate categories (age class, sex, geographic area, and if appropriate, vaccination status) so as to provide a representative cross-section of animals captured during annual census trapping. While maintenance of the same set of collared animals across years (with replacement as animals die or collars become nonfunctional) has benefits such as facilitating collection of long-term data on individuals and reduction of annual collaring effort, it can also introduce bias into survival estimates, because the composition of individual risk profiles of the sampled animals changes over time (Zens and Peart 2003). As time passes, animals with higher risk die first, and those with lower risk remain in the sample, causing the sample to be increasingly skewed toward animals with lower risk. Therefore, a new sample of animals should be collared each year. However, rather than selecting "against" animals that have previously been collared, we suggest that animals be selected regardless of their current collar status. That is, if a collared animal is captured and was selected for collaring, it simply gets a new collar. If it was not chosen for collaring, the old collar can be removed or it can be left on if continued tracking of the individual would benefit other research projects. If the decision is made to leave the collar on, survival data on this animal should continue to be recorded in the event that its data can be used in future hazard analyses; however, this animal may not be appropriate to include in the annual survival estimates.

We assume that most, if not all, of the 40 animals to be included in survival monitoring will be captured and collared as part of the annual census trapping efforts. Therefore, we expect that very little trapping will occur specifically to collar animals for survival monitoring. A small amount of targeted trapping may, however, be necessary after annual (summer) trapping, if

[1] It may be advisable to develop a "decision tree," which can be readily used by field personnel to make decisions on which animals to collar.

inadequate representation or numbers of animals were captured, or if it is desirable to target previously collared animals to remove collars (e.g., as the collar approaches the end of its battery life). We also assume that animals trapped during the annual census trapping effort will likely be sampled for health screening by the Fox Health TEG, but recognize that additional targeted trapping may be required for health screening depending on health sampling protocols, or if there is a desire to vaccinate animals in specific geographic areas.

Analysis of survival data should include estimation of annual survival rates using the known fate model in program MARK, with model selection to consider differences by age, sex, geographic area, etc., using information theory methods. A hazard analysis may also help identify covariates of survival (e.g., Cox and Oakes 1984).

Pulse rates on radiocollars should be reduced to prolong battery life of collars, but should be rapid enough to allow location of carcasses, perhaps at 40 beats per minute (bpm). Ideally, bpm should be adjusted so that collar battery life coincides with scheduled annual trapping (12 or 24 months, rather than 18 months), to minimize the number of collars with batteries expiring between capture efforts. Field personnel should be equipped with standardized mortality investigation forms and digital cameras. Personnel should be on-call to immediately locate and collect dead foxes, and an established protocol should be maintained for shipping carcasses to UC Davis as quickly as possible. All carcasses should promptly be submitted for necropsy, even if field investigations determine the cause of death to be eagle predation.

3 Data Management and Integration

3.1 Standardization of Databases

Data generated from long-term monitoring are valuable for understanding factors influencing island fox populations. Monitoring is also intended to generate comparable data for comparisons and analyses across islands. It is therefore critical that data be collected, stored, and managed in a standardized manner that will allow for accurate and efficient use, both within and across islands.

3.2 Integration of Fox Monitoring Data with Other Monitoring Data

To generate data useful for exploring the dynamics of fox populations, monitoring should also include standardized and long-term collection of other biotic and abiotic data.

Climate and local weather patterns

Measures of precipitation, temperature, relative humidity, and wind should be recorded and maintained for use in analyses. Climate patterns may influence island fox population dynamics by impacting survival, reproduction, distribution, and dispersal. Climate patterns can influence food resources of foxes, including fruits, mice, and invertebrates. Precipitation, temperature, relative humidity, and wind can also impact probability of capture during trapping sessions, and thus are important covariates for inclusion in statistical analyses of population dynamics

Abundance and distribution of other species

To increase knowledge about the interactions of island foxes with their habitat, competitors, predators, and prey, long-term data on nonnative species (e.g., dogs, cats, elk, deer, rodents) and native species (rodents, skunks, birds, herpetofauna) is extremely important. Many of these species have been studied at some time on at least one of the islands, and long-term monitoring programs exist for a few. However, it would be most beneficial if a monitoring protocol were established to collect standardized long-term data on these species, even if this is only an annual index of abundance (or density) and distribution on each island, combined with periodic population estimates, if feasible. We also recommend focused research modules related to some of these species (Sections 4-8).

Disease profiles among other species

As disease is one of the primary threats to island foxes, the Fox Health TEG has developed guidelines for monitoring pathogens in island foxes. Understanding the etiology of diseases will be facilitated by establishing disease profiles for other species on each island, including feral cats and dogs, bats, rodents, marine mammals, and skunks, for which very little local data exist (e.g., Bakker et al. 2006). Ideally, medical testing should be incorporated into any existing research, collection, or monitoring programs that include animal handling. Some data (such as presence of some parasites) may be obtainable by non-invasive methods such as scat collection. Because of the high costs of disease screening, the Fox Health TEG should refine and prioritize recommendations for data collection.

Vegetation characteristics

Vegetation on all five islands has been extensively impacted by grazing of livestock and introduced ungulates. Although many of these animals have been removed in recent years, it will take years for vegetation to recover. As vegetation recovers, there will be changes in vegetation composition, cover, and structure, all of which could impact fox habitat use, distribution, and densities. We therefore recommend establishing or continuing standardized vegetation monitoring programs on each island. Ungulates still remain on some islands, with some planned removals in coming years, which will provide additional research opportunities related to herbivore impacts on island ecosystems (Sections 4-8).

Other environmental health parameters

Numerous factors can influence the health of the ecosystems upon which island foxes rely. The following represent a subset of factors that could impact island foxes and their ecosystem, and which should be monitored as part of a long-term program on the islands for which these factors are relevant:

1. Water quality and distribution on the island. As climate patterns change and human visitation to the islands increases, it is possible that the quantity and quality of fresh water sources could be modified.
2. Presence, type, and levels of rodenticides or other toxic substances. Records on rodenticide use should include the type of poison used, the amount applied, the type of dispensing device used, and the location where rodenticide was applied. In addition, all dead foxes, whether suspected of dying from rodenticide poisoning or not (e.g., road-killed individuals), should be tested for rodenticide levels. This information should be stored in one comprehensive file available to veterinarians monitoring island fox health.
3. Road traffic (temporal and spatial patterns of traffic volume and velocity). This information, when paired with data on spatial and temporal patterns of road kills and island fox movement in relation to roads and other habitat features, will help identify management alternatives. For example, if road kills tend to be more frequent at a particular time of day or during one season of the year, such data would be helpful in discerning whether this increase is due to changes in traffic volume or velocity vs. changes in fox movement patterns.
4. Human visitation and activity (location, type of activity, etc.). Fox distribution could be influenced by changing human activity, either through avoidance or attraction to human use areas. We therefore recommend maintaining long-term data, at the minimum in the form of an index, on human numbers, if such a monitoring protocol is not already in place. This may pertain primarily to islands with high tourist visitation rates (Santa Catalina and Santa Rosa islands) but would also apply to military activity on San Nicolas Island and areas open for camping on Santa Cruz and San Miguel islands.

Data such as the above should be compiled and managed in a way that allows future integration and analyses with fox population data. To increase the usefulness of datasets, collection and management of data should be coordinated across islands.

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):

<u>Parameters for tracking recovery</u>

- 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.

<u>Parameters for island-specific management decisions</u>

- 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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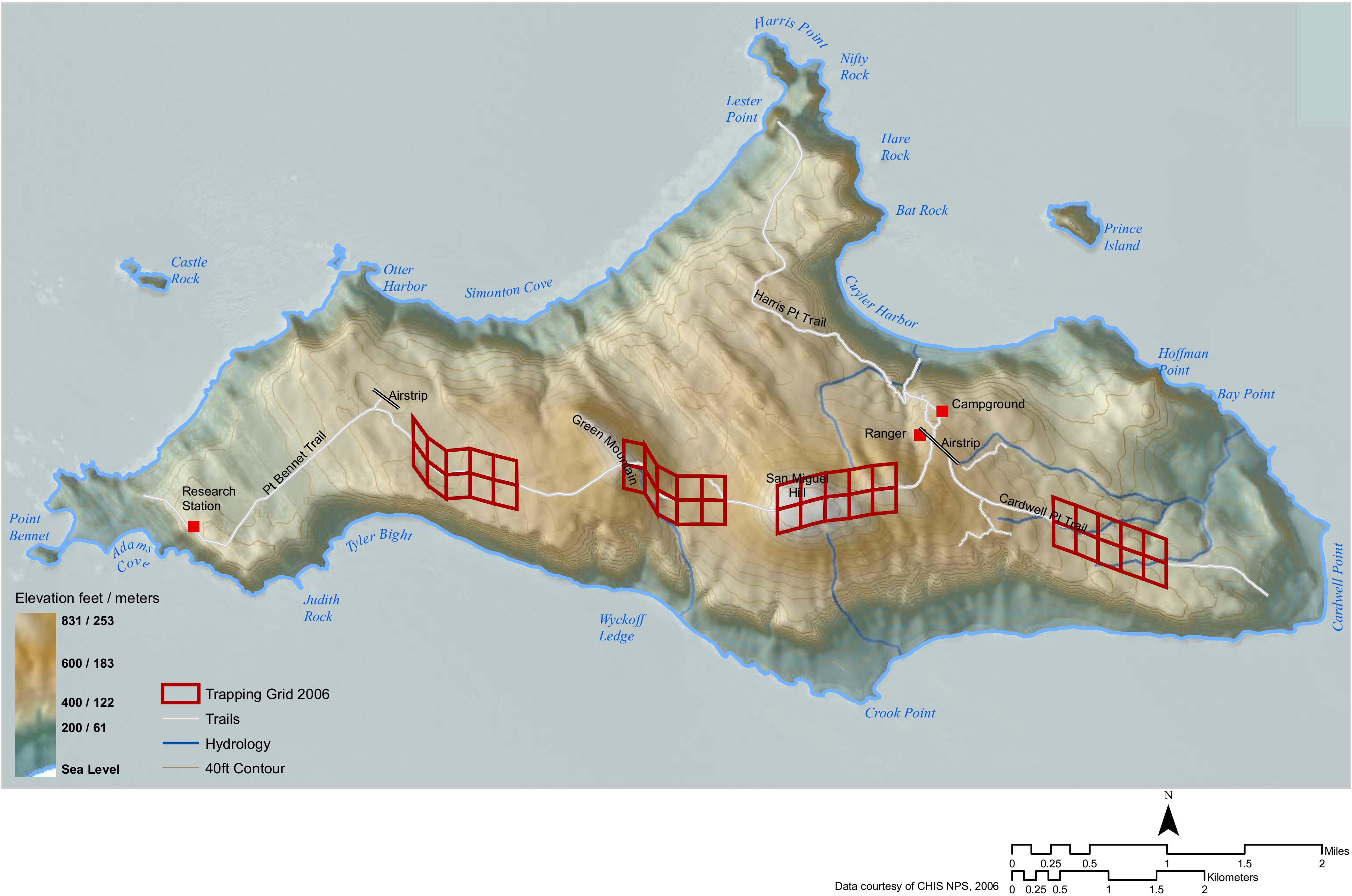
San Miguel Island

Map 4-1: Existing Trapping Grids



Data courtesy of CHIS NPS, 2006

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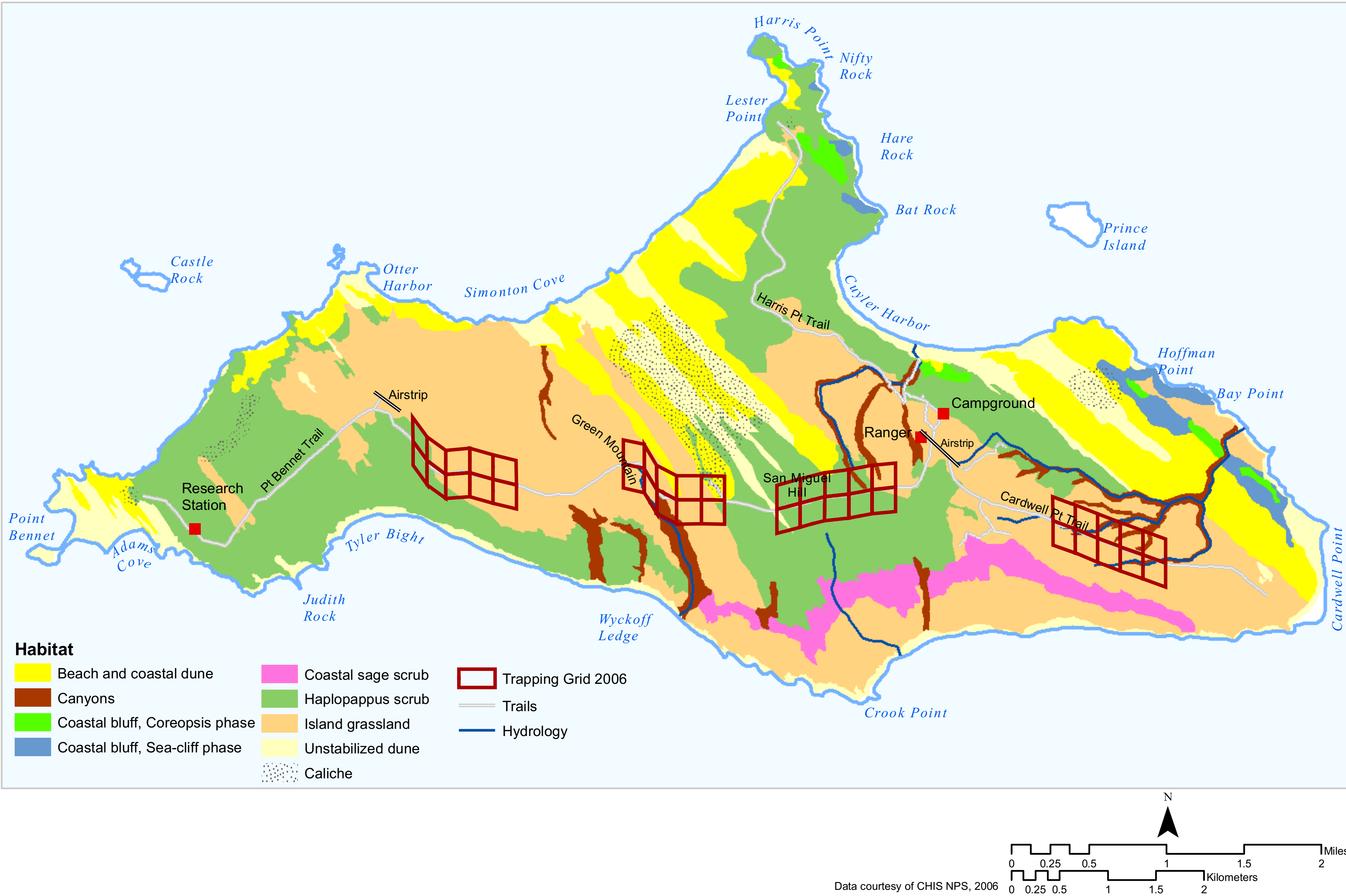
Map 4-2: Existing Trapping Grids in Relation to Vegetation



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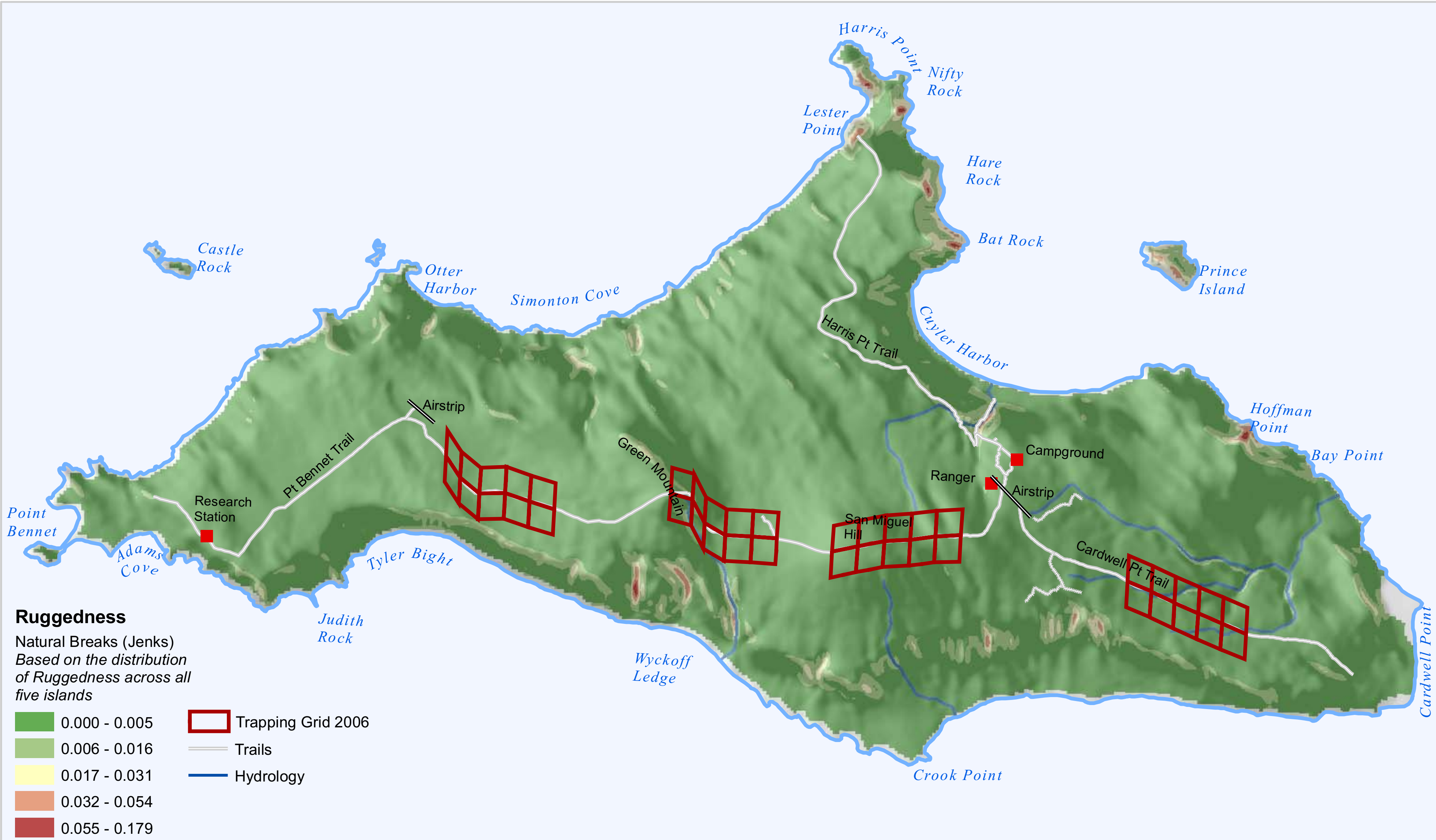
Map 4-4: Existing Trapping Grids in Relation to Ruggedness



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

N

0 0.25 0.5 1 1.5 2 Miles

0 0.25 0.5 1 1.5 2 Kilometers

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

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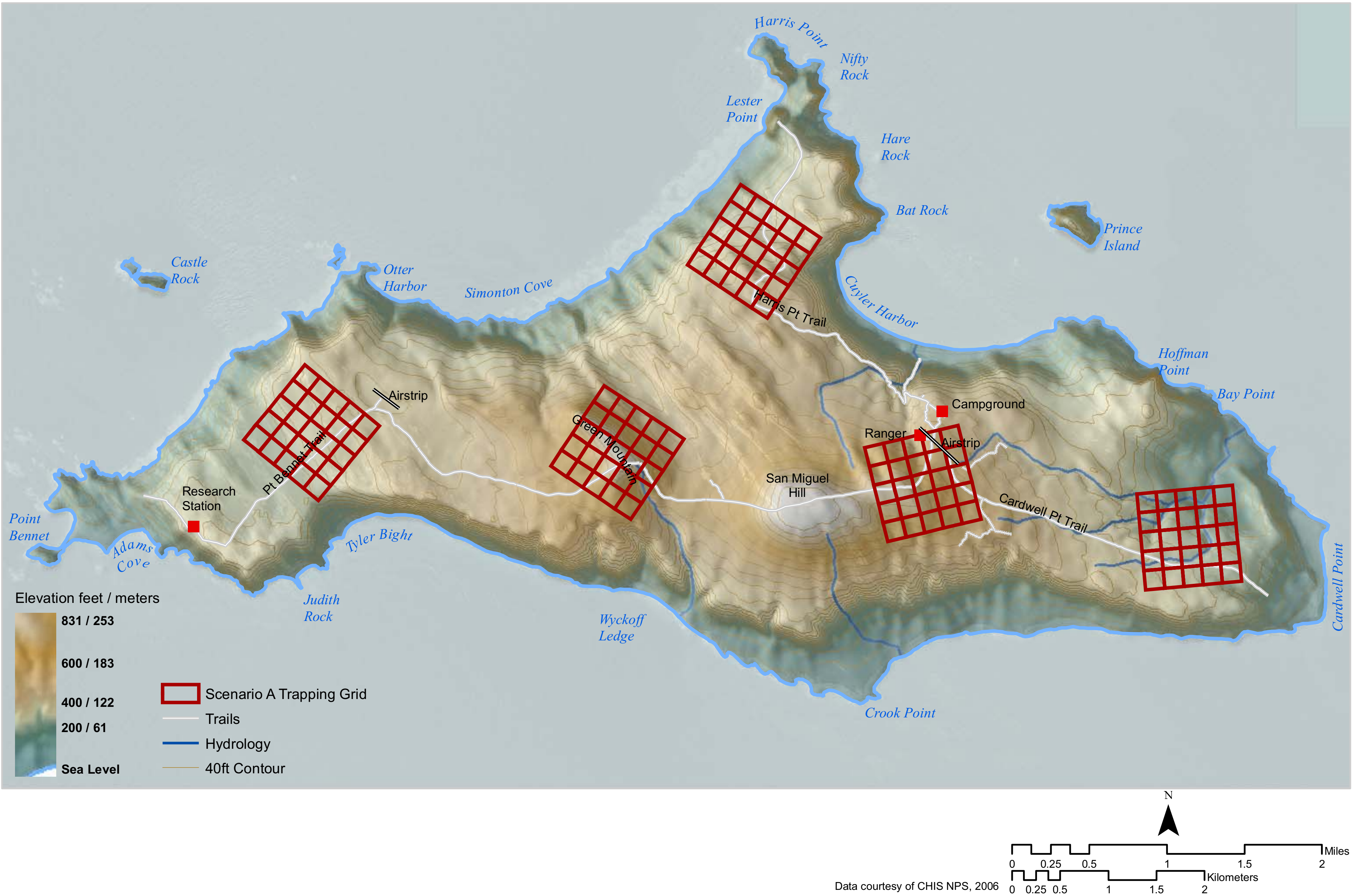
San Miguel Island

Map 4-5: Trapping Scenario A



Data courtesy of CHIS NPS, 2006

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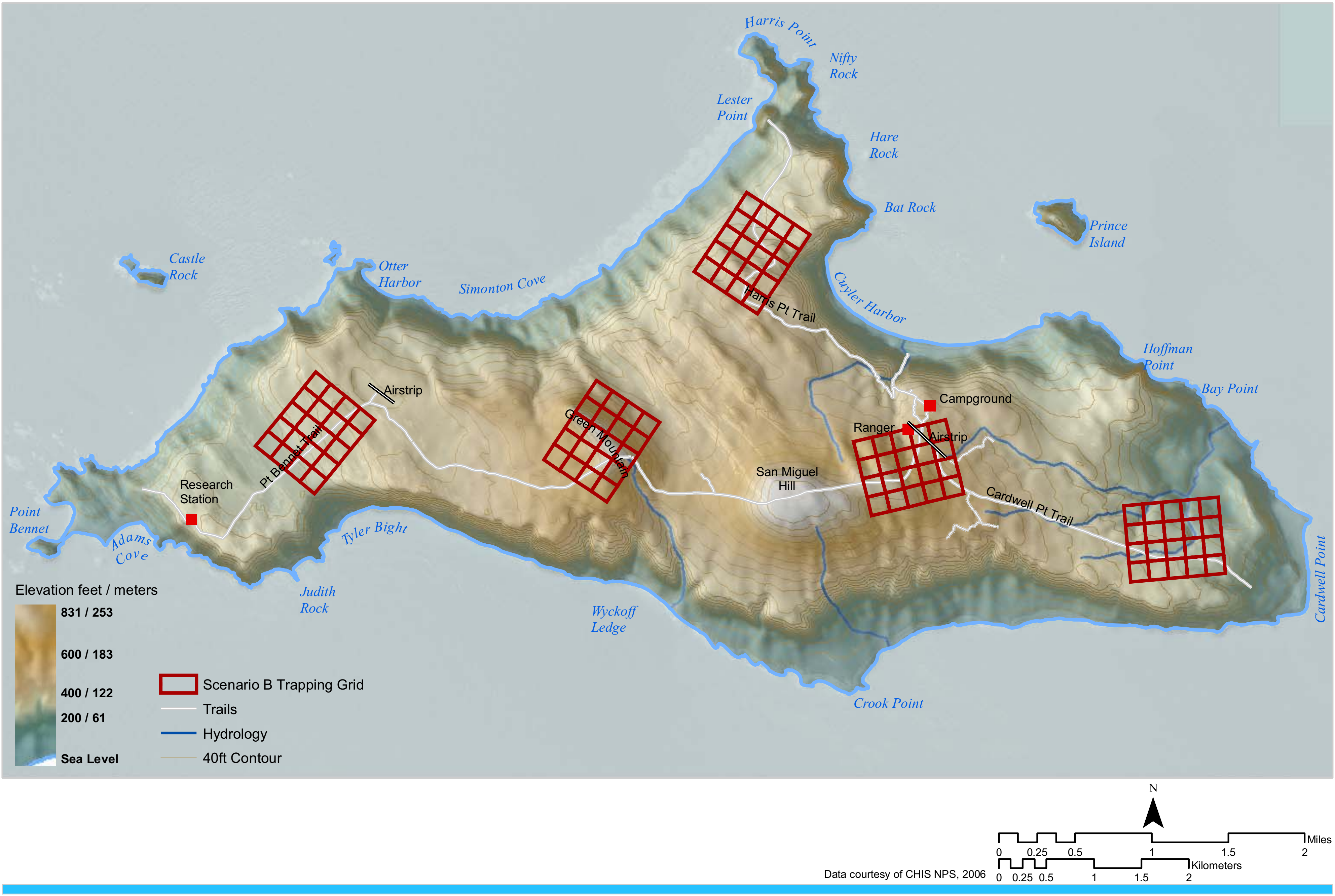
Map 4-6: Trapping Scenario B



Data courtesy of CHIS NPS, 2006

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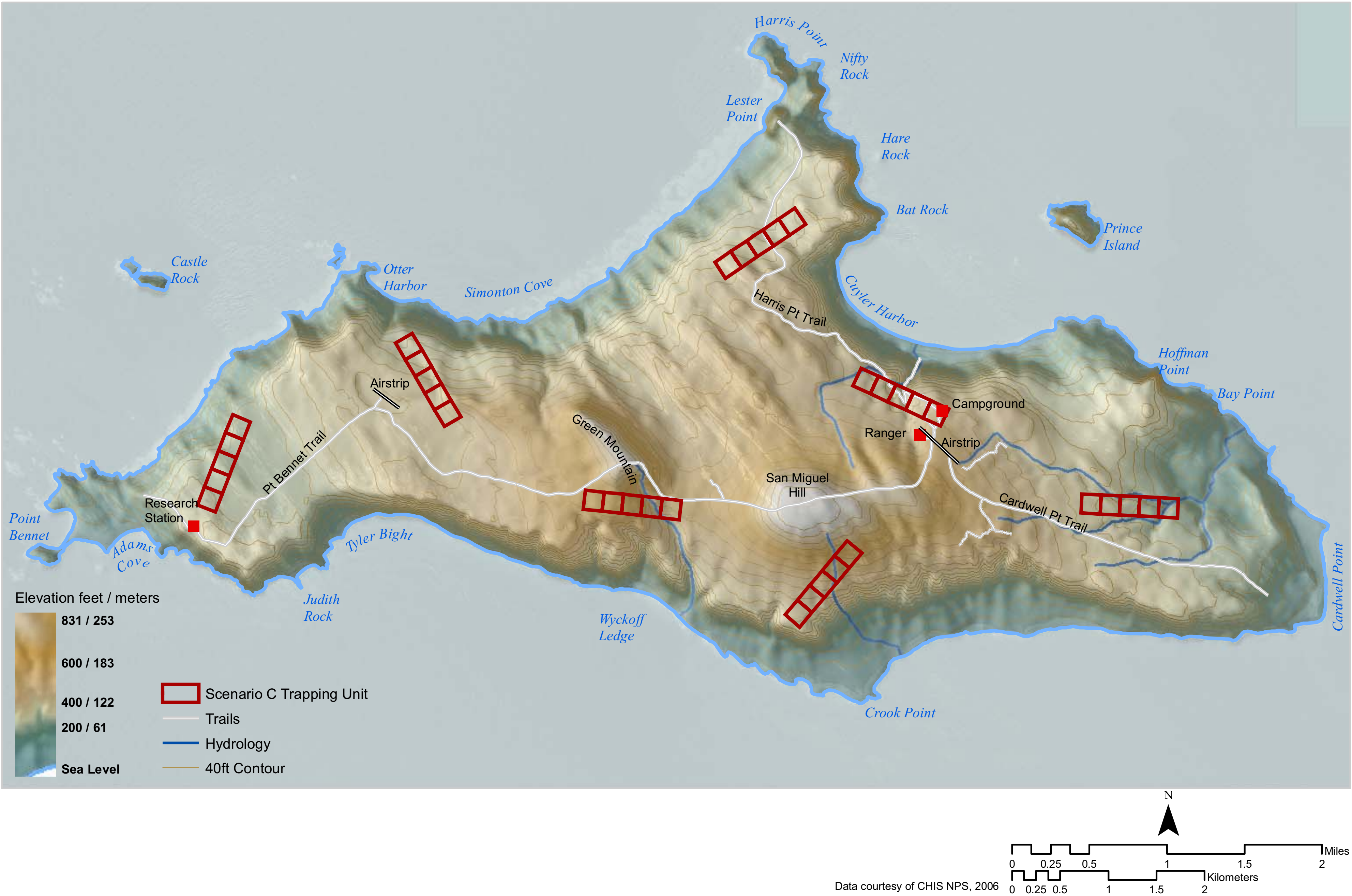
Map 4-7: Trapping Scenario C



Data courtesy of CHIS NPS, 2006

5 A Monitoring Plan for San Nicolas Island Foxes

San Nicolas Island, with an area of 58 km^2, is the fourth smallest of California's eight Channel Islands, and is the second smallest of the islands to be inhabited by island foxes (Laughrin 1973, Juola et al. 2002, Table 1-1). It is also the farthest island from the mainland, located 98 km (61 miles) from Ventura, California (Schoenherr et al. 1999; Map 1-1). San Nicolas Island is approximately 13 km long and 5.5 km wide, and has an elevational range of sea level to 278 meters (Juola et al. 2002; Map 5-1).

Vegetation on the island is primarily coastal scrub (42% of island area), barren areas (24%), and grassland habitat (12%; Schmidt and Garcelon 2003; Map 5-2). Topographically, the island is represented by a large plateau with arroyos cutting down to the shoreline. Freshwater sources are found in the form of several springs and temporary canyon streams (Laughrin 1973). San Nicolas Island has been administered by the U.S. Navy since 1945 and is closed to the public.

San Nicolas Island provides important habitat for a variety of shorebirds and marine mammals. For example, dune areas provide important nesting habitat for endangered snowy plovers (*Charadrius alexandrinus*), which have experienced large population declines due to loss of dune habitat along the mainland coast (Schoenherr et al. 1999). Marine mammals that inhabit the island include California sea lions (*Zalophus californianus*), northern elephant seals (*Mirounga angustirostris*), and harbor seals (*Phoca vitulina*; Schoenherr et al. 1999). Sea otters (*Enhydra lutris*) were reintroduced to the island during 1988-1990, and there were approximately 40 individuals on the island in 2005 (Bentall 2005).

5.1 San Nicolas Island Foxes

Foxes on San Nicolas Island are classified as a unique subspecies (*Urocyon littoralis dickeyi*; Moore and Collins 1995), which is listed as Threatened by the State of California (CDFG 1987). This subspecies and island foxes on San Clemente Island are the only two populations of island foxes not currently listed as endangered by the USFWS.

The current (2005) estimate of adult island foxes on San Nicolas Island is 402 (95% confidence intervals = 384-479), and annual reported adult estimates during 2000-2004 ranged from 381 to 614 animals (Roemer et al. 2002b, Juola et al. 2002, Schmidt and Garcelon 2003, Schmidt and Garcelon 2004, Garcelon and Schmidt 2005, Schmidt et al. 2006). This suggests that the population has been fairly stable since 2000, and that densities are relatively high compared to those on other islands (Juola et al. 2002). Grid-specific estimates of lambda estimated from trap data collected during 2000-2005 also suggest that the population has been stable since 2000 (Schmidt and Garcelon 2004, Schmidt et al. 2006).

However, several pieces of evidence suggest that this subspecies has decreased to very low numbers in the past. Anecdotal observations suggest that very few foxes were observed on the island during the 1950s (Schmidt et al. 2006). In addition, Laughrin (1978) documented an apparent decline during surveys conducted in 1971, 1974, and 1977, with very low trap success and few observations of fox sign during the 1977 survey compared to previous surveys. These observations led Laughrin (1978) to warn that the San Nicolas Island fox population was at critically low numbers in 1977. Subsequent data collected by Kovach and Dow (1981), Kovach (1982), and Kovach and Dow (1986) suggest that fox numbers and distribution on the island increased during 1980-1985, with population sizes for 1984 and 1985 estimated at 560-600 and 475-515, respectively (Kovach and Dow 1986). These observed patterns, of a population decline to very low numbers followed by a population increase, are consistent with the results of a recent examination of major histocompatibility complex (MHC) diversity in foxes on San Nicolas Island. This analysis and simulation of MHC, which contains genes that influence disease resistance and kin recognition, suggests that the population went through an extreme bottleneck of less than 10 individuals during the past 10-20 generations (Aguilar et al. 2004). The causes of the observed and inferred decrease(s) are not known, however.

Since 2000, San Nicolas Island has supported some of the highest population densities observed in any populations of island foxes (Garcelon and Schmidt 2005, Schmidt et al. 2006). It is not known how this density compares to the carrying capacity of the island, and it is possible that the population may be at or above carrying capacity. If the latter case, density-dependent factors may cause an eventual population decrease. Regardless, the small size of the island imposes a relatively small carrying capacity and an accompanying small population size, which places this subspecies at an increased risk of extinction relative to larger populations on larger islands. Potential threats to the future persistence of this subspecies include disease, negative interactions with feral cats, and other threats associated with human presence and activities.

Disease risk is considered one of the primary threats to all island fox populations, because their isolation on islands has minimized or prevented their exposure to diseases. A low prevalence of parasites may be another indication that San Nicolas Island foxes have had low disease exposure (Schmidt and Garcelon 2003). They also have low genetic diversity, which typically increases a population’s susceptibility to novel diseases. For this reason, introduction of novel diseases, particularly those introduced by dogs and other animals, presents a constant and serious risk.

Although the link between health and body condition and past population trends is not clear, it is worth noting that (a) trapped foxes were all in good condition in 1971, (b) foxes trapped and observed during 1974 during an apparent population decline were not in good health, with many cases of mange and deformities observed, (c) the three foxes trapped in 1977 after this apparent decline were in good condition, and (d) foxes trapped in 1980 were in excellent condition (Laughrin 1978, Kovach and Dow 1981). Foxes captured during 2000-2005, a period of apparent population stability, were found to be generally healthy except for several cases of minor injuries (both old and due to capture), torn ears and tails, and some external parasites such as fleas. Juola et al. (2002) indicated that San Nicolas foxes tested in 2001 exhibited 80% prevalence for canine distemper virus (CDV) antibodies. This finding is peculiar, as recent (post-1974) losses due to disease had not been documented, while exposure to CDV would have been expected to cause a noticeable die-off, as observed on Santa Catalina Island (Timm et al. 2000). It is possible that either foxes on San Nicolas Island were exposed to a less virulent strain of CDV, or that they had been exposed to another Morbillivirus which may have cross-reacted in the highly sensitive test used at the Cornell lab (Juola et al. 2002).

A number of human-associated factors may have impacted San Nicolas Island foxes in the past, and some continue today. Livestock grazing likely impacted the fox population in past years, through changes to vegetation (an overall reduction in plant abundance and diversity) and possibly via competition for forage plants. The first sheep ranchers arrived on San Nicolas Island in 1857 (Schoenherr et al. 1999). By 1890, more than 30,000 sheep were being grazed on the island, and by 1930 trees and bushes had disappeared from over two-thirds of the island. (Schoenherr et al. 1999). The last sheep rancher left the island in 1941 and the last sheep were removed in 1943 (Schoenherr et al. 1999), but the impacts of past grazing remain to this day.

The presence of feral cats may influence the viability, abundance, and distribution of island foxes. Feral cats occupied San Nicolas Island in low numbers prior to 1952, mostly along the northern slopes of the island from the west end to, but not beyond, the living compound (Kovach and Dow 1981). Laughrin (1973) suggested that feral cats could have negative impacts on island foxes, but reported that by 1971 and 1972 most of the cats had been removed from the island. However, upon returning to the island in 1977, he noted that cat numbers had increased *alarmingly*, and that cat distribution had expanded from 1971, when they were observed primarily near the living compound, to 1977 when cats were commonly seen in many parts of the island. During this same time period, he noted an apparent decline in fox numbers (Laughrin 1978). Kovach and Dow (1981) also noted that additional introductions of cats in 1973 or 1974 likely resulted in a large population in and near the living compound, and foxes were no longer observed in these areas in following years.

Cats may compete with foxes through exploitation competition by cats using a limited resource such as prey or denning sites, or through interference competition, by cats actively or passively displacing foxes and thereby reducing fox access to a resource (Brian 1956). Observations suggest that cats can be dominant and aggressive to island foxes, especially to young foxes (K. Brock, U.S. Navy, pers. comm., Laughrin 1978). Laughrin (1971) noted that fox predation on birds was highest during the spring when fox pups were present, and that competition for this prey item may be particularly high during this time period. Kovach and Dow (1981) noted spatial segregation between cats and foxes, with low fox densities in areas where cat densities were highest. These authors further speculated that the fox carrying capacity for San Nicolas Island would be increased if cats were removed from the island (Kovach and Dow 1986). Recent field data suggest that cat densities may be relatively low in recent years, with only one cat captured during 888 trap-nights in 2003 (Schmidt and Garcelon 2004, Schmidt et al. 2006).

Although San Nicolas Island has been closed to the public for at least 61 years, there were several hundred U.S. Navy personnel on the island by the early 1970s (Laughrin 1973), and human activities have likely impacted foxes to some degree since then. Since 2000, 56% of discovered mortalities (n = 25) were attributed to vehicular collision (Schmidt et al. 2006). This may, however, have over-estimated the proportion of deaths due to vehicular collision, because opportunistic discoveries of mortalities are more likely along or near roadways. Other human-related mortalities include one fox that was struck by an aircraft, one fox that was locked inside a building, and one fox that was electrocuted (Kovach and Dow 1981, Schmidt et al. 2006). The impact of vehicular collisions on the population viability is currently unknown because the actual number of foxes killed or injured is unknown. Kovach and Dow (1981) suggested that additional research should examine survival and causes of mortality.

It has also been suggested that artificial feeding near human compounds, which lasted for a number of years and ended in the summer of 1974, may have artificially increased density and caused animals to become dependent on this food source (Laughrin et al. 1974 cited in Kovach and Dow 1981). A large number of carcasses were found in late 1974 after the artificial feeding was stopped, near living compounds and other areas where artificial food sources had been placed, and Laughrin et al. (1974, cited in Kovach and Dow 1981) suggested that only animals near these areas were influenced by the cessation of artificial feeding in previous months. However, observations of an apparent island-wide decline in fox numbers between 1971 and 1977 bring this conclusion into question (Kovach and Dow 1981), and to date it is not clear how artificial feeding may have influenced the fox population.

5.2 Monitoring Objectives

As described in Section 2.1, the following monitoring objectives were identified for San Nicolas Island:

<u>Parameters for tracking population status</u>

- Annual estimate of island-wide population size, with an 80% confidence interval. The point estimate should ideally 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.

<u>Parameters for island-specific management decisions</u>

- Cause-specific mortality rates by age and sex, considering all causes of mortality.
- Habitat- and site-specific density.
- 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 (all islands).

5.3 Past and Current Monitoring

5.3.1 Summary of Past and Current Protocols

The first quantitative survey of island foxes on San Nicolas Island in 1971 examined demographics, distribution, and food habits (Laughrin 1973, 1978). During that 4-day study, transect trapping at four locations (40 traps total) was combined with visual searches for foxes, fox sign, and scat samples. The study generated preliminary data on trap success, age class and sex ratios, density, distribution, general health, and diet. Laughrin (1973) reported a trap-success of 72%, one of the highest observed that year on six islands sampled. The study did not provide an island-wide population estimate, as it did not sample the island adequately (Laughrin 1973).

Further similar field work, with variations in transect locations and trap numbers, was completed in 1974 and 1977, with efforts in 1977 augmented with a nighttime spotlight census during 3 nights (Laughrin 1978). These efforts provided additional data on trap success, density, distribution, age class and sex ratio, general health, diet, and data on cat distribution and relative abundance (Laughrin 1978).

In 1980, Kovach and Dow (1981) began a more comprehensive study to examine abundance, distribution, habitat use, food habits, and interactions between foxes and cats. This study included grid trapping during spring and summer, additional grid and transect trapping during fall, and collection of scat samples for diet research. During spring/summer field sessions, 12 trapping grids were established to sample a wide range of vegetation and topographical variation. Eleven of the 12 grids had dimensions of 3x10 traps, while the 12th grid was 2x12 traps. Traps were spaced 160-320 meters apart, and most grids were trapped for 3 nights. During fall trapping sessions, one transect of 7 traps and two smaller grids, comprised of 9 and 20 traps, spaced at 320 meters, were trapped for 1 night. This study provided information on reproduction and recruitment, estimates of home range size, diet composition, general body condition and health, sex ratios, age structure, relative habitat selection, density by various vegetation types and geographical location on the island, and limited information on causes of mortality. A population estimate was also generated by extrapolating trapping results and movement data.

Additional trapping was conducted during 1981-1985, using techniques similar to those used by Kovach and Dow (1981) but with some variation in trap locations (Kovach 1982, Kovach and Dow 1986). Starting in 1982, more detailed data were collected on disease presence, via the collection and analysis of blood samples. Population estimates were generated using Lincoln-Petersen's estimate (Kovach and Dow 1986).

In 1998, Roemer (1999) trapped foxes along a different set of transects on San Nicolas Island and on the five other islands inhabited by island foxes as part of a cross-island comparison of density. He set traps approximately 200 meters apart, 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 exhibited the same abundance trends.

After a lapse of nearly 15 years of little formal research on San Nicolas Island foxes, Roemer et al. (2002b) initiated a standardized mark-recapture design to evaluate fox demography on the island. As part of this study, they established three trapping grids in 2000, attempting to place the grids in three different vegetation types. The Skyline grid was placed in grassland and coastal scrub, the Tuft's grid was placed in coastal scrub, and the Redeye grid was placed in coastal scrub and inland dune habitat types. Traps were spaced 250 meters apart, and each grid was trapped for 6 consecutive nights (Table 5-1). These three grids have been trapped annually since 2000 (Roemer et al. 2002b, Juola et al. 2002, Schmidt and Garcelon 2003, Schmidt and Garcelon 2004, Garcelon and Schmidt 2005, Schmidt et al. 2006).

Blood and scat samples are collected from a sample of captured animals each year, and veterinarians have examined subsets of animals, beginning in 2003 (Schmidt and Garcelon 2004). Trapping at the above three grids therefore provides data on age structure, sex ratios, health and body condition, and disease exposure. In addition, grid-specific estimates of adults and density were derived from trap data using closed population models in program CAPTURE during 2000-2004, and program MARK starting in 2005 (Schmidt et al. 2006). An annual island-wide population estimate is generated by extrapolating estimated fox density in each sampled vegetation type by the area of the vegetation type. Vegetation types not trapped or not adequately sampled, and considered to be poor fox habitat, are assigned an arbitrary low density of 1 fox/km^2, and this number is added to estimates of sampled vegetation types.

In an attempt to efficiently monitor radiocollared animals for survival and movement patterns, a remote telemetry system is being developed and tested on San Nicolas Island (D. Garcelon, IWS, pers. comm.). This system, comprised of multiple receivers located throughout the island, currently monitors signals multiple times per day to determine if an animal's collar is in mortality mode. As the system is refined and improved, it may provide locational data on each animal and transmit this information remotely to researchers (D. Garcelon, IWS, pers. comm.).

Table 5-1. Size of three trapping grids and dates trapped during 2000-2005

Year Trapped	Skyline (5 x 10 = 50 traps)	Tuft's (5 x 10 = 50 traps)	Redeye (6 x 8 = 48 traps)
2000	July 14 – 19	Aug. 18 – Aug. 23	Sept. 12 – Sept. 17
2001	July 06 – 11	June 28 - July 03	July 14 – July 19
2002	July 17 – 22	July 09 – July 14	June 30 – July 05
2003	July 21 – 26	June 28 – July 03	July 11 – July 16
2004	July 07 – 12	June 29 – July 04	Oct. 6 – Oct. 11
2005	July 07 – 12	June 27 – July 02	July 16 – July 21

5.3.2 Representation Analysis of Current Trapping Protocols

To determine how well existing trapping protocols sample habitat variability on the island, we conducted representation analyses using both univariate and multivariate techniques to compare habitat variability sampled by existing trapping grids with island-wide habitat variability (Appendices B and G).

Based on univariate analysis, trapping grids sample areas that are less steep, less rugged, farther from the shoreline, and closer to paved roads and developed areas than island-wide areas (Appendix B; Maps 5-3 and 5-4). In addition, sampled areas are closer to riparian habitat and vernal pools (habitat features which we used as an index of potential freshwater sources). Relative to the availability of different vegetation communities, trapped areas appear to over-represent coastal scrub and inland dunes and under-represent barren areas and *Coreopsis* vegetation. Some of these differences may not be biologically relevant, as some differences were small relative to documented fox movement patterns (e.g., distance to freshwater) or were not relevant given the small absolute difference (e.g., slope and ruggedness; Appendix B).

However, other differences such as the distance to shoreline, distance to paved road, and differences in vegetation associations between trapped and island-wide areas could cause biases in parameter estimation if fox density, habitat use patterns, or survival vary with these factors.

We also examined habitat representation of the trapping scenario 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 G). Current grid trapping locations substantially under-represent steep, rugged shoreline far from roads, development, and drainages and vernal pools. Nearly 50% of the variation in habitat attributes is captured by the principal component describing this multivariate habitat type, and trapped areas show the most significant bias in habitat representation for this type. Once accounting for topography linked to proximity to shoreline and development, however, steep and rugged terrain was not under-sampled. Interior areas were generally over-sampled, regardless of terrain or distance to drainages and pools. Interior areas far from development tended to be under-sampled.

The Skyline and Tufts grids both sample similar habitat characteristics and are skewed towards developed interior areas, while the Redeye grid provides coverage of gentle shoreline areas. Trapping areas appear to sample the major vegetation types roughly in proportion to their occurrence on the island, although *Coreopsis* vegetation is clearly under-sampled. When examining multivariate habitat attributes by vegetation type, overall patterns of representation are relatively constant across vegetation types. Interestingly, the lack of bias in sampling steep rugged drainages arises partly from over-sampling this habitat type within barren vegetation and under-sampling it within inland dune. The over-representation of remote interior areas near drainages and pools is due in part to over-sampling of this habitat type within grassland vegetation as well as failure to trap significantly in many of the vegetation types that predominate in shoreline areas, such as beach, coastal dune, and *Coreopsis*.

5.3.3 The Ability of Existing Protocols to Meet Current Objectives

Previous and ongoing studies of island foxes on San Nicolas Island have produced a wealth of valuable information, including data on population trends, estimates of density, age structure and sex ratios, and animal health. In this section we discuss the adequacy of existing protocols to address current monitoring objectives (Section 5.2). We recognize that previous 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 needs, 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 Nicolas Island, as grid trapping can provide relatively robust local estimates of abundance and density. In addition, the current three 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 three grids collectively sample approximately 35% of the island. Although grids were originally positioned to represent several major habitat types, they each represent a mix of vegetation communities, and collectively do not represent major vegetation types in proportion to their representation on the island (see Section 5.3.2 and Appendices B and G). This is due primarily to under-sampling of barren areas and *Coreopsis* vegetation, which together comprise about 36% of the island, and over-sampling of coastal scrub and possibly inland dune areas. Other features such as distance to shoreline and distance to roads may also influence fox densities. Our representation analyses indicate that, for several habitat features, the current grids don't sample the island in proportion to habitat variability on the island (Appendices B and G). Although it is likely impossible to sample all habitat variability on San Nicolas 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 habitat representation with a revised trapping protocol, ideally involving a randomized method of distributing trap effort.

The current method of assigning an arbitrary value of 1 fox/km^2 to unsampled vegetation types, when in reality the density in these areas is not known, may result in population estimates with low accuracy, as acknowledged repeatedly by researchers working on San Nicolas Island (Roemer et al. 2002b, Schmidt and Garcelon 2003, Schmidt and Garcelon 2004, Garcelon and Schmidt 2005, Schmidt et al. 2006). For example, Schmidt and Garcelon (2004) acknowledged the lack of sampling in barren and *Coreopsis* areas, and suggested additional sampling via transect trapping along roads in these areas to provide density estimates for these vegetation types. Using more and slightly smaller grids could increase representation and possibly allow for habitat- or vegetation-specific density estimates. This approach should therefore improve population estimates for the entire island.

Based on simulation modeling, the current protocol does provide a density estimate with adequate precision when densities are modeled at 4 or 9 foxes/km^2. If density were to decrease to 1 fox/km^2, however, precision would be decreased (Section 4.4.2). At any density, extrapolating estimates across unsampled habitats may introduce some error.

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. Current grids do not appear to represent the island adequately (Appendices B and G). It may be possible to infer general population trends on the island, especially if all three grids exhibit similar patterns; however, it is also possible that habitats not represented by the grids could be experiencing different trends than sampled areas.

To improve grid-specific trend data, protocols should be standardized across years. Although two of the grids have been trapped at fairly consistent times of the year, the Redeye grid has been trapped at various times between June and October (Table 5-1). Timing of trapping may influence age structure, sex ratios, reproduction data, animal weights, and distances moved (Kovach and Dow 1981). As acknowledged by Juola et al. (2002), this may influence interpretation of data and trends. Trapping all grids at similar times of the year, although more difficult, would allow more robust comparisons of data across grids.

Changes in how density is calculated may also influence estimates. Any changes in analytical methods and models chosen should be clearly presented in future reports so readers can better understand observed variation in trends. Ideally, past data should be re-analyzed with revised methods and presented with confidence intervals, so the reader can evaluate how much variation was due to changes in methods versus actual changes in population trends. We recommend that density estimates be made using maximum likelihood spatially explicit capture-recapture methods implemented in program DENSITY, or closed population mark-recapture models implemented in program MARK. In either case, information theory should guide model selection (Burnham and Anderson 2002).

Survival and cause-specific mortality rates

Survival rates can be estimated from annual capture data. However, annual trapping data do not reveal mortality causes and do not facilitate immediate management response in the event of a disease outbreak or sudden increase in predation. Beginning in 2006, up to 60 radiocollared foxes have been tracked, in part with the use of a remote telemetry receiver system (D. Garcelon, IWS, pers. comm.). This sample size exceeds the recommended sample size and, therefore, robust data on survival and cause-specific mortality rates should be obtainable. The success of this approach will depend on (a) whether signals can be checked frequently enough to find, recover, and send carcasses to UC Davis in time for meaningful necropsies, and (b) whether enough collared foxes can be maintained on the island long term (Section 2.4.2). In addition, it is assumed that the foxes in this study are distributed widely across the island, and that age/sex classes are represented adequately. This will allow the most comprehensive monitoring of survival and allow researchers to differentiate between patterns of survival, dispersal, and capture probabilities. For example, the lower percentage of male pups captured as adults in subsequent years caused Schmidt and Garcelon (2003) to speculate that male pups may have lower survival when, in fact, this pattern could be due to sex-based differences in dispersal or capture probabilities, as also acknowledged by these authors (Schmidt and Garcelon 2003).

Density of foxes in major habitat types

One monitoring objective for San Nicolas is to estimate density by major habitat types to help guide management. Although the three capture grids were originally placed to represent major vegetation types, capture data from the grids have typically not been used to provide vegetation-specific densities, because each grid represents mixed vegetation communities, and calculating densities for portions of a grid is problematic. As mentioned above, habitat attributes other than vegetation type may also influence habitat quality. Extracting these data from existing grids would be difficult as well, e.g., traps located near roads versus traps located far from roads.

5.4 Monitoring Protocols for San Nicolas Island

5.4.1 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 Nicolas Island must consider the following specific issues:

1. Although San Nicolas Island has relatively gentle terrain, and an extensive road system allows access to most of the island, there are several areas, primarily along the southern coastline, that are inaccessible due to steep and unstable slopes and bluffs (Maps 5-3 and 5-4). Archaeological middens may also restrict field activities in some areas.
2. Much of the shoreline is closed to entry seasonally (January-September) to protect nesting shorebirds and breeding marine mammals.
3. Localized and temporary closures occur due to military activities. These do not follow a set schedule; however, Navy Environmental Department staff are typically notified in advance.

5.4.2 Candidate Trapping Protocols

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

We first evaluated the feasibility of island-wide random trapping, due to the statistical robustness of this method (Section 2.4.1; Box 2-2). Using a plausible range of fox movement patterns and capture probabilities, we simulated the number of traps and trap-nights required to obtain enough recaptures to generate a population estimate with the desired precision. We considered two variations of this approach: (a) random placement of traps across the island each night and (b) systematic and even placement across the entire island with the entire grid shifted in a random direction by up to one-half the inter-trap distance each night. Based on analyses for San Miguel Island (Appendix K, Addendum A), the second variation provided higher precision for a given number of traps and trap-nights, and we therefore examined only this approach for San Nicolas Island. Simulation results indicated that adequate precision could be obtained if 58 traps spaced at 1,000 meters were trapped for 11-14 nights, depending on density (modeled here at 4 and 9 foxes/km^2) and on detection parameters modeled (Appendix L). During actual trapping sessions, the number of trap-nights could be adjusted depending on the number of recaptures obtained. We present this scenario as San Nicolas Island Trapping Scenario A (Map 5-5).

We also evaluated precision resulting from existing protocols (existing grids and number of trap-nights) and variations of these protocols involving different number and size of grids as well as different number of trap-nights. Given a particular trap layout and duration, 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 1, 4, and 9 foxes/km^2, with the latter similar to the current estimated density of 9.4 foxes/km^2. Detection scenarios were set at plausible values, based on the high current density on San Nicolas Island and at a best estimate of detection scenarios, generated by V. Bakker using actual trap data from multiple years and multiple islands, and the program DENSITY.

Simulation results suggested that 33 recaptures would be necessary to obtain a mean CV($\hat{D}$) = 20%, and 40 recaptures was recommended as a design target to ensure that the desired CV was consistently attained (Appendix M). Our goal was, therefore, to identify scenarios that would approach 40 recaptures, although we also considered less intensive efforts considered more economically and logistically feasible. For all scenarios, 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 grids on San Nicolas generated an adequate number of recaptures (thereby producing an estimate within the targeted precision) when densities were modeled at 4 and 9 foxes/km^2, but the number of recaptures fell below the targeted number when density was reduced to 1 fox/km^2 (Appendix L, Table L-3). In addition, the three existing grids potentially under-represent some habitat types on the island (Appendices B and G). We therefore explored the option of using a larger number of smaller grids with the same overall total number of trap-nights. We evaluated expected precision of five 6x6 trapping grids, trapped for 5 nights, and found that this scenario also provided an adequate number of recaptures at densities of 4 and 9 foxes/km^2, but also failed to meet the target precision when density was 1 fox/km^2 (Appendix L, Table L-3). At current densities, this scenario would provide a density estimate with CV($\hat{D}$) of approximately 15%, and this precision would drop to a CV($\hat{D}$) of approximately 28% if density were to decline to 1 fox/km^2 (Appendix L, Table L-3). In terms of precision, this scenario therefore provides the same benefits as the existing scenario, but it tends to represent habitat variability more adequately. At density of 1 fox/km^2 both scenarios produce density estimates with lower than desired precision. However, at that density, there would only be about 60 foxes on the island, and it is likely that many of these would be radiocollared. Thus, although the minimum number of foxes known to be alive (MNKA) can not be used to estimate population size, it would be relatively close to the true number of foxes and may serve to shorten the confidence intervals on $\hat{N}$ estimates by truncating the lower interval. We therefore present this scenario (five grids) as San Nicolas Trapping Scenario B. We produced a suggested map of this scenario by placing (and orienting) the five grids randomly on the island, with the following rules: (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 (Map 5-6). 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 therefore 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 (Appendix L and M?). This evaluation was conducted in the same manner as evaluation of the larger grids; however, a range of densities was also evaluated (Appendix M). Figure M-7 in Appendix M indicates the precision expected at varying densities, given different numbers of trapping units, with CV($\hat{D}$) = 20% representing approximately 33 recaptures. 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 CV($\hat{D}$) ≤20%. Our goal was to identify logistically feasible scenarios that would obtain approximately 33 recaptures, as indicated by CV($\hat{D}$) = 20% in Figure M-7 (Appendix M).

Simulation results suggested that at the current density of 9.4 foxes/km^2, four units would likely provide adequate precision (expected CV($\hat{D}$) ≤20%; Appendix M). However, four units would likely not sample habitat variability adequately on the island. In addition, if fox density were to drop to 1 fox/km^2, more than12 units would be required to obtain 20% precision. We therefore decided to use more units, even at high densities, but with the option of reducing trap-nights per unit when densities (and hence recaptures) are high enough to yield 20% precision. The limited size of the island allows for a maximum of nine units if units are to be ≥1,500 meters apart. As with the spacing of grids, units could be placed closer to each other but 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 the current density, the use of nine 2x6 trap units, trapped for 6 nights each, would likely generate a density estimate with CV($\hat{D}$) <18%, while a precision of approximately 37% would be expected if density dropped to 1 fox/km^2 (Appendix L). We present this scenario as San Nicolas Trapping Scenario C and mapped this scenario by randomly placing units as for Scenario B (Map 5-7).

The three San Nicolas Island scenarios (A, B, and C), as well as the existing protocol, can all produce a density estimate of adequate precision at high fox densities, but produce lower precision estimates when densities are low. There is no correct answer on choice of protocol, as there are trade-offs in each case. Scenario A may produce the most robust population estimate as well as the best representation of habitat variability. However, Scenario A may be more complex and labor-intensive to implement due to frequent moving of traps. Scenario B provides good precision but will likely not sample the island as completely as Scenario A, although it is expected to sample the island more completely than the current protocol. Scenario C will most likely provide the best habitat representation after Scenario A, and will provide good precision at moderate to high densities, but will produce a slightly lower precision at low densities. The expected precision of any of the 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.).

One of the monitoring objectives for San Nicolas Island is to estimate density by major habitat types to help guide management. This may be most feasible with Scenario A or C, as these scenarios will sample habitat variability on the island most completely. Under these two scenarios, the influence of various habitat covariates could potentially be examined using multivariate analyses. Research on habitat selection and home-range size, using locational data from radiocollared animals, would also shed light on differences in habitat quality across the island landscape (Section 5.5.3).

5.4.3 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 methods and compared two of the candidate protocols (Scenarios B and C) to habitat variability in island-wide areas and those sampled by the existing protocol (Appendices B and G). It is assumed that Scenario A would effectively sample the island because the approach distributes and shifts traps widely across the island, and we therefore did not include Scenario A in our analyses.

Univariate analyses (Appendix B) indicate that all three scenarios (existing trapping protocol, Scenario B, and Scenario C) sample areas that differ statistically from random points on the island for all habitat measures examined. However, statistical differences do not necessarily indicate biologically relevant differences. For example, statistical differences were found in slope and ruggedness, with trapping areas representing areas with lower slope and ruggedness, but absolute differences were small and may not influence trapping results, as discussed in Appendix B. Trapped areas also sampled areas closer to paved roads, developed areas, and sources of freshwater, but in all cases the actual differences were small relative to fox movement patterns, so these differences may not bias trapping. It is possible, however, that small differences in distance to roads may influence trap results, if fox density differs near roads. Under-sampling of areas close to the shore may bias trapping results if fox density is different close to the shore than in other areas. Scenario C most closely resembles the island in terms of distance to shore and to roads, and in representation of vegetation categories, and overall provides a better representation of the island than the existing protocol or Scenario B, although differences do exist between Scenario C and island-wide areas.

Multivariate analyses (Appendix G) indicate that existing grid trapping has under-represented dry, rugged, remote shoreline, although once accounting for topography linked to proximity to shoreline and development, steep and rugged terrain was not under-sampled. Interior areas far from drainages are currently somewhat over-sampled. Proposed trapping scenarios also under-represent steep and rugged terrain of all types and modestly over-represent interior terrain of all types. Overall, Scenario C appears to do a slightly better job representing multivariate habitat types on the island. 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.

We suggest that future habitat selection studies should be conducted to examine if these differences might bias trap results. In addition, density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to assure that these biases do not bias monitoring results.

5.4.4 Survival and Cause-Specific Mortality Monitoring

San Nicolas Island's small size and relatively gentle terrain should make frequent monitoring of radio signals via ground monitoring feasible. An existing road network allows covering most of the island by motor vehicle, making monitoring of signals time-efficient. Short hikes (most <800 meters) would allow access to vantage points for checking signals near steeper bluffs on the southern side of the island.

Although ground monitoring of signals appears to be feasible on San Nicolas Island, the use of remote telemetry receivers could be considered as a supplement to direct ground monitoring (Section 2.4.2). A remote telemetry system currently being developed and tested on San Nicolas Island (D. Garcelon, IWS, pers. comm.) or a similar system in which receivers are placed on towers as described by Spencer et al. (2006) may provide useful options. 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 Nicolas Island. U.S. Navy regulations may limit the allowable height of the towers, however, and this may influence the range of each tower. A viewshed analysis would be needed to determine the necessary number and most effective placement of towers, based on their height, and to determine portions of the island that would not be monitored as part of the remote system. Prior to the viewshed analysis, the detection range of collars should be confirmed in the field.

Ground monitoring and monitoring by remote receivers are both feasible options for San Nicolas Island, and the decision between the two will depend on the availability of field personnel versus the cost of tower construction and equipment purchase. Remote systems can greatly reduce the need for field personnel; however, personnel will still need to be present on the island to respond to and investigate mortalities.

We suggest that survival estimation be performed with the known fate model in MARK, rather than the simple Kaplan-Meier estimator.

5.5 A Tiered Approach for Population Monitoring

5.5.1 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: Mark-recapture sampling using the entire island as the effective trap area, with 58 traps trapped for 11-14 nights, for a total of 638-812 trap-nights annually (Map 5-5)
- Scenario B: 5 grids of 6x6 traps, trapped for 5 nights, for a total of 900 trap-nights annually (Map 5-6)
- Scenario C: 9 units of 2x6 traps, trapped for 6 nights, for a total of 648 trap-nights annually (Map 5-7).

Trapping should 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. 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.

5.5.2 Recommended Monitoring for Survival and Cause-Specific Mortality

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

1. Annually radio-collar at least 40 foxes with mortality-sensing collars, according to the guidelines in Section 2.4.2. These foxes should be widely distributed across the island. 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 targeted follow-up trapping may be necessary if inadequate numbers or composition of animals are captured, or if previously collared animals must 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. Continue to explore the option of a remote monitoring system to augment or replace monitoring efforts on the ground, if a cost analysis and/or evaluation of personnel availability suggest that remote monitoring would be more cost-efficient on this island.
    - 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).
4. If the above investigations warrant the use of remote telemetry on towers, construct towers and install and test the automatic recording system.
5. Explore using GPS collars to monitor survival (Section 2.4.2).
6. Have personnel on call, and on the island, to immediately locate and investigate mortalities, and develop a standard protocol for transporting carcasses to UC Davis for necropsy.

5.5.3 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 Nicolas Island include:

1. Habitat and space use. Habitat selection and space use should be studied to examine behavioral and demographic patterns relative to roads, human activity, vegetation types, water sources, shoreline areas, and cat densities. 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). In addition, studies to examine home range size, movement patterns, and dispersal, especially at various densities, will help determine if there are habitat quality differences that could lead to source-sink dynamics. For example, recapture of animals in grids other than their original capture grid suggests that there is a tendency to move away from the Tuft's and Redeye grids and toward the Skyline grid, indicating movement from higher density areas to areas of lower density (Schmidt and Garcelon 2003, Schmidt and Garcelon 2004). The presence of radiocollared animals (for survival monitoring) will greatly facilitate such studies.
2. Ecological relationships with feral cats. Cat density and distribution may influence the viability, abundance, and distribution of island foxes, and previous studies have suggested an inverse relationship between densities of foxes and cats (Kovach and Dow 1981, 1986). Further studies could provide valuable information on competition (e.g., for prey, den sites) and how interactions between the two species vary across seasons, years, and population densities. Current plans to begin a cat removal program on San Nicolas Island may provide opportunities to study the influence of cat removal on foxes.
3. Reproduction and early pup survival. Although annual trap data may provide some information on reproduction (e.g., proportion of captured females exhibiting signs of reproduction), further research is needed on reproduction, early 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.
4. Traffic. Temporal and spatial patterns of traffic volume and velocity, when paired with data on spatial and temporal patterns of road kills and island fox movement in relation to roads and other habitat features, will help identify management alternatives. If road kills tend to be more frequent during one season, such data could help discern whether this is due to changes in traffic volume or velocity vs. changes in fox movement patterns.
5. Vegetation. A vegetation monitoring protocol, consisting of 36 established transects monitored at approximately 5-year intervals, exists on San Nicolas Island. We suggest that such monitoring be continued and that the island-wide vegetation map be updated every 5-10 years. As part of this effort, field work should be conducted to measure vegetation height, structure, and composition at pre-determined sites to track changes due to habitat recovery, climate change, and human activity. These data will be useful for understanding temporal and spatial patterns of fox habitat use.
6. Rodenticide use. The current San Nicolas Island Pest Management Plan and Pest Contract do not allow the use of rodenticides, and nuisance rodent trapping around

developed areas is restricted to the use of snap traps. However, given the possibility that an individual might apply rodenticides illegally, all dead foxes, whether suspected of dying from rodenticide poisoning or not (e.g., road-killed individuals), should be tested for rodenticide levels. This information should be stored in one comprehensive file available to veterinarians monitoring island fox health.

7. Disease and health**.** Although standardized disease and health monitoring will be conducted every year, 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.

8. Effectiveness of remote telemetry stations. Existing field studies should be continued to refine the use of remote monitoring systems to augment or replace survival monitoring efforts on the ground. This should include 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).

9. 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 capture-mark-resight 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 be explored further.

10. 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.

11. 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 additional non-fox data that should be routinely monitored and integrated with fox data.

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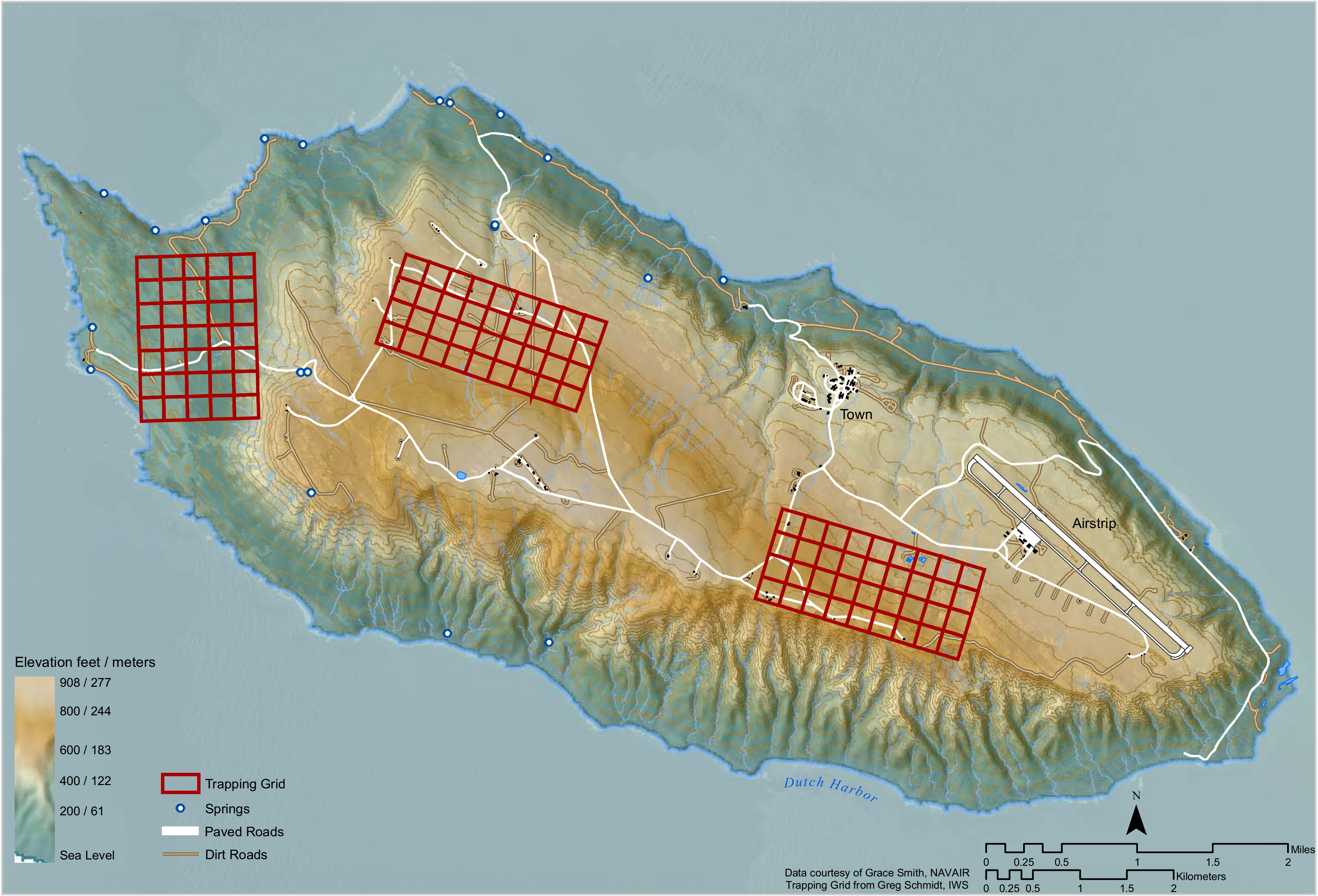
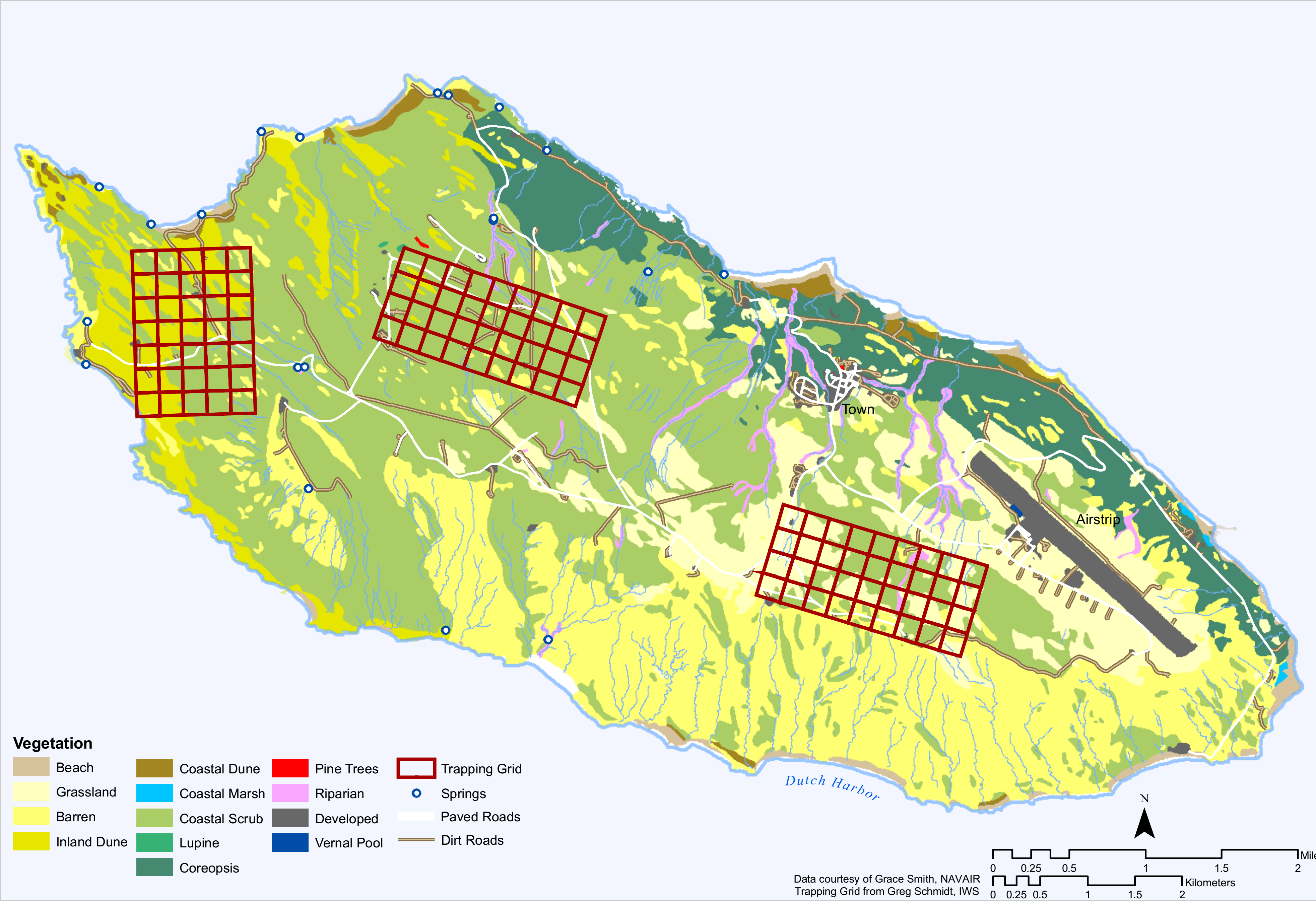
San Nicolas Island

Map 5-1: Existing Trapping Grids



San Nicolas Island

Map 5-2: Existing Trapping Grids in Relation to Vegetation



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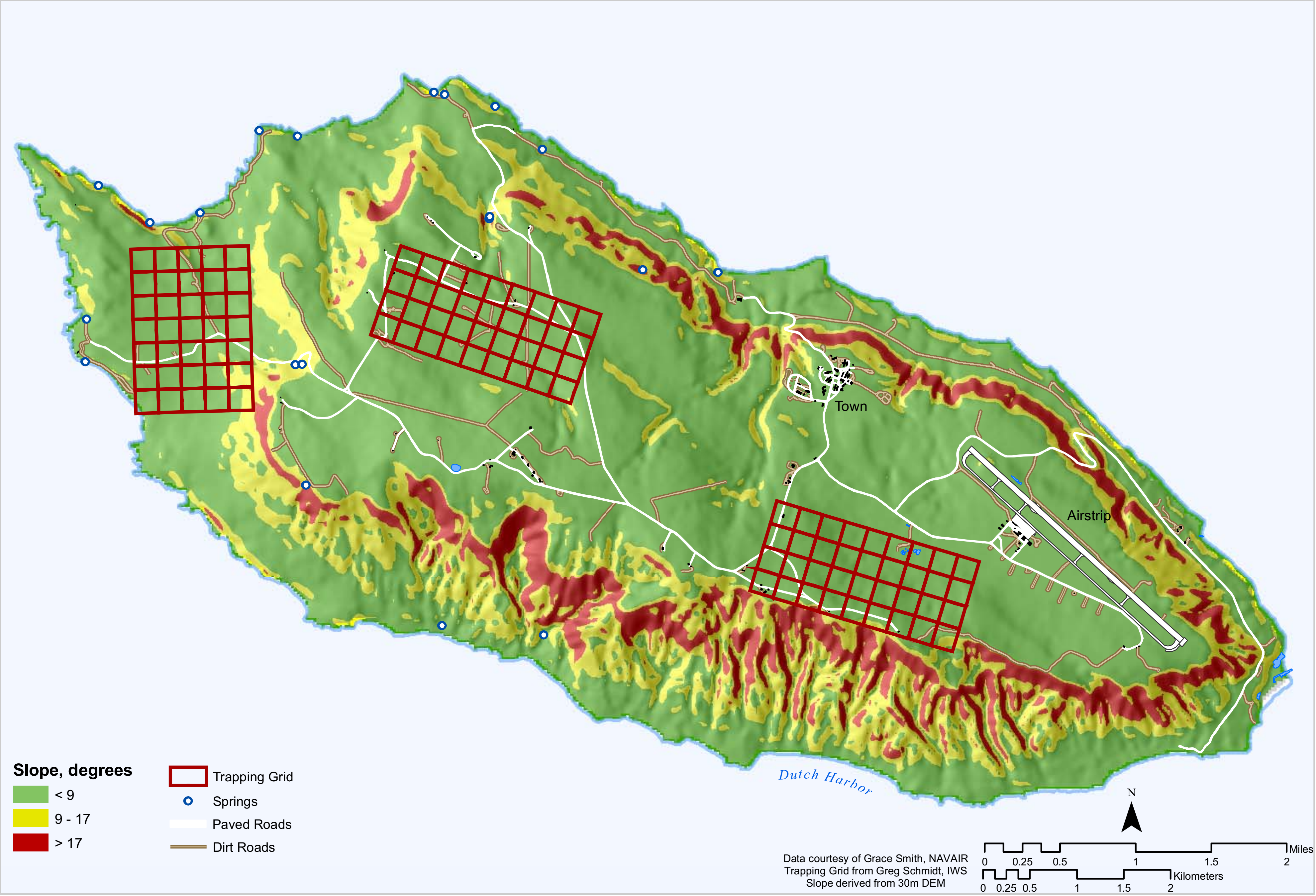
Map 5-3: Existing Trapping Grids in Relation to Slope



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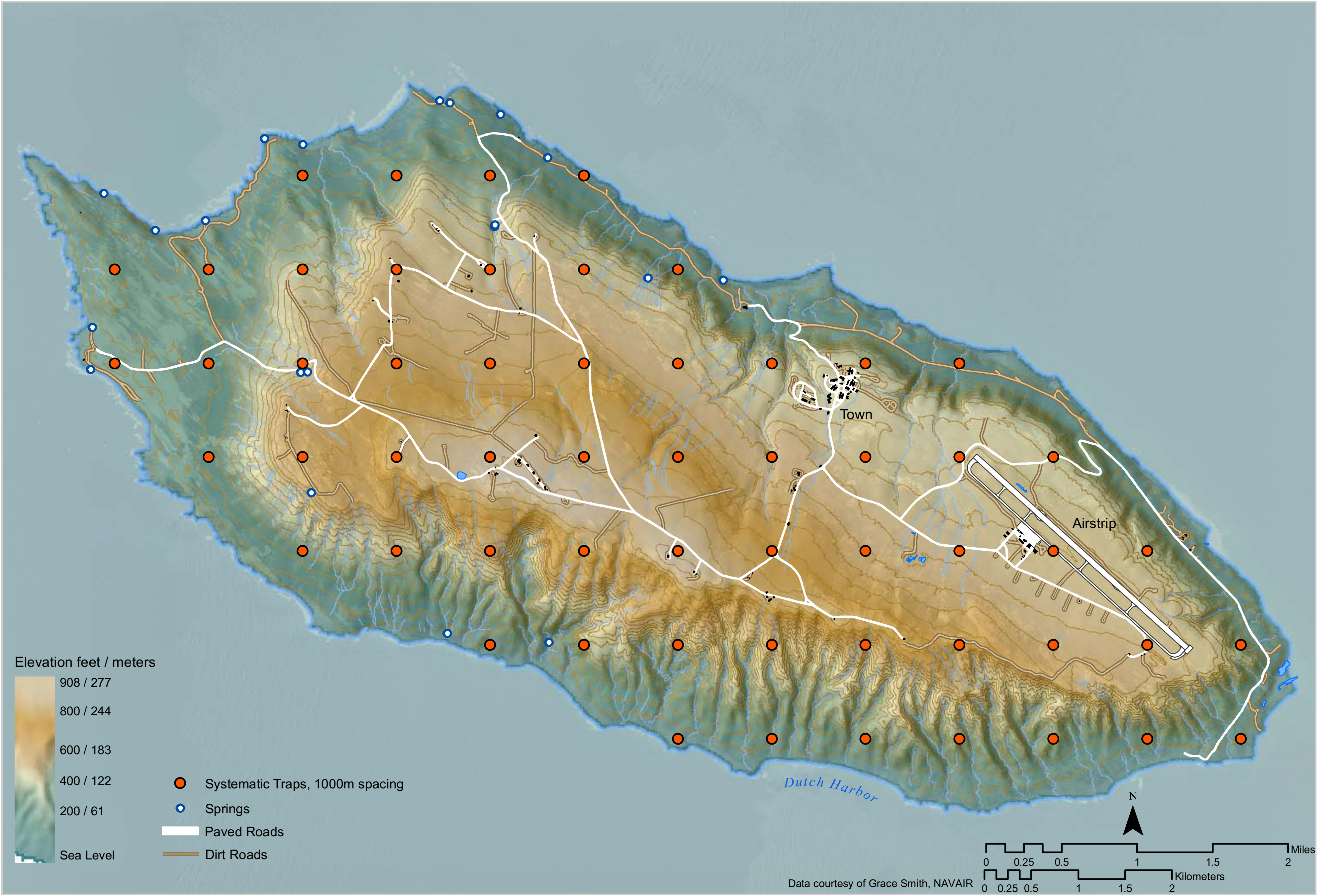
Map 5-4: Existing Trapping Grids in Relation to Ruggedness

San Nicolas Island

Map 5-5: Trapping Scenario A



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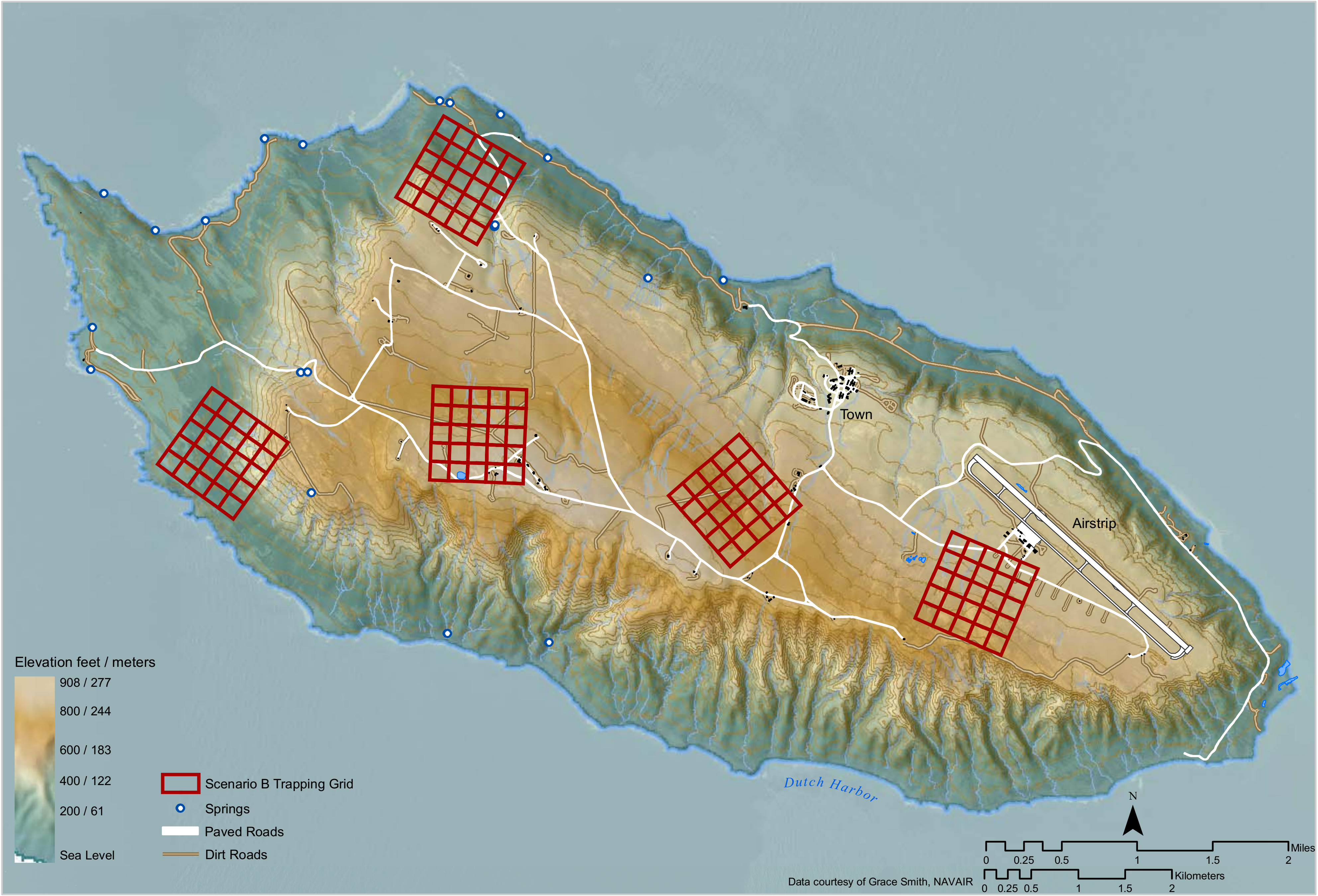
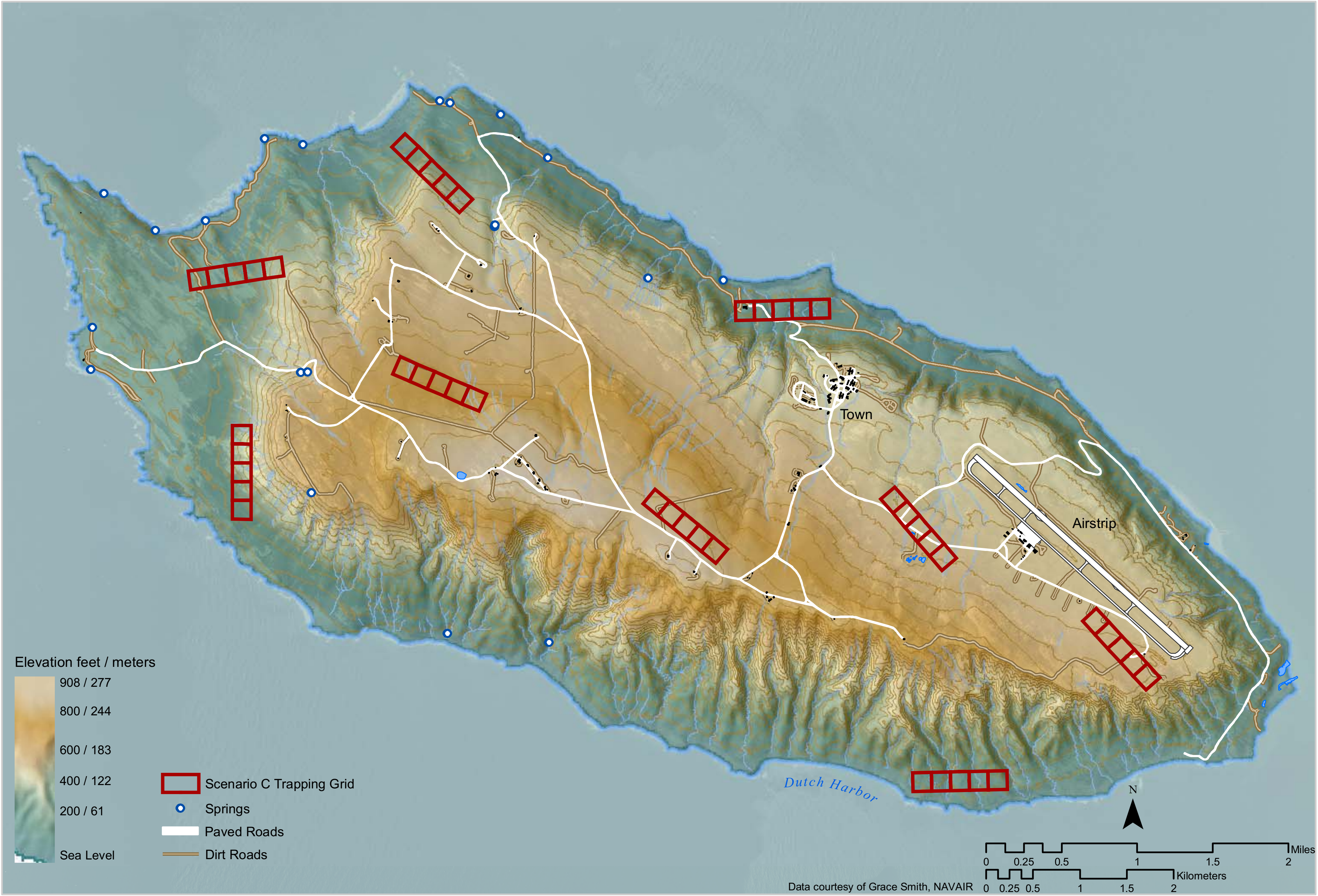
San Nicolas Island

Map 5-6: Trapping Scenario B



San Nicolas Island

Map 5-7: Trapping Scenario C



6 A Monitoring Plan for Santa Catalina Island Foxes

Santa Catalina, with an area of 194 km^2, is the largest of the four southern Channel Islands and is the southern island located nearest the mainland (Laughrin 1973; Table 1-1, Map 1-1). The island is approximately 35 km (22 miles) long and 13 km (8 miles) wide at its widest point, but it is <800 meters (0.5 mile) wide at the narrow isthmus near the town of Two Harbors (Laughrin 1973; Map 6-1). The narrow isthmus separates the island into the West End, comprising 16% of the island, and the East End, comprising 84% of the island (Kohlmann et al. 2003).

The Santa Catalina Island Conservancy (SCIC) owns most of the island, which has a total human population of over 3,600, with most living in the incorporated city of Avalon and the remainder living in the unincorporated town of Two Harbors. Because it is easily accessible from the mainland and offers a variety of recreational opportunities, Santa Catalina has the largest human population of all the Channel Islands and hosts up to a million visitors per year (Schoenherr et al. 1999). Although most human activity is concentrated in Avalon and Two Harbors, most interior portions of the island are accessible to visitors, and the perimeter shoreline is popular with visitors arriving by private boat.

Ranching has been an important part of the history of Santa Catalina Island, with goats, cattle, horses, and sheep introduced in the 1800s, and pigs introduced in the 1930s (Schuyler et al. 2002). Although many of these were removed by 1972, goats and pigs still exist on the island (Laughrin 1973, Schoenherr et al. 1999). In addition, American bison (*Bison bison*) and mule deer (*Odocoileus hemionus*) were introduced during the 1920s and 1930s (Lott and Minta 1983). Both species as well as other nonnative animal species, including blackbuck antelope (*Antelope cervicapra*) and feral cats, are still found on the island (www.catalinaconservancy.org, accessed January 22, 2007; Coonan 2003).

Santa Catalina Island is topographically and botanically diverse, with elevations ranging from sea level to over 610 meters (2,000 feet, Laughrin 1973). Due to complex topography created by numerous deep canyons and steep precipitous cliffs along the shoreline, this island is second only to Santa Cruz in the diversity of habitats it supports (Laughrin 1973). Major vegetation communities on the island are: coastal sage scrub, representing 39% of the island and dominated by sage (*Salvia apiana* and *S. mellifera*), cacti (*Opuntia* spp.), lemonadeberry (*Rhus integrifolia*), and sugarbush (*R. ovata*), island chaparral, representing 30% of the island and dominated by chamise (*Adenostoma fasciculatum*), island scrub oak (*Quercus pacifica*), ceanothus (*Ceanothus* spp.), and island mountain mahogany (*Cercocarpus betuloides* var. *blancheae*), and grassland, representing 20% of the island and now dominated by nonnative grasses such as oats (*Avena fatua*), California brome (*Bromus carinatus*), and ripgut brome (*B. diandrus*, Schoenherr et al. 1999, Timm et al. 2002; Map 6-2). There are several freshwater sources including perennial springs, small streams, and man-made reservoirs on the island (Laughrin 1973).

6.1 Santa Catalina Island Foxes

Foxes on Santa Catalina Island are classified as a unique subspecies (*Urocyon littoralis catalinae*; Moore and Collins 1995). Fox populations on several of the Channel Islands, including Santa Catalina Island, have experienced periods of low density (Laughrin 1973). Catalina Island foxes were reported to be abundant in 1886, rare in 1893, and nearly extinct in 1917 (Grinnell et al. 1937). Fox numbers were reported to be very low in 1971, triggering the original classification of "rare" by CDFG (Laughrin 1973, 1980). In 1972, 3 nights of trapping (60 trap-nights) produced only two captured foxes, and a search of the island produced little sign (Laughrin 1973). Trapping in 1975 suggested a slight increase in abundance, but the researcher concluded that numbers were still low relative to densities on other islands (Propst 1975).

In 1988 the population on Santa Catalina Island was still considered to be the most imperiled of the six populations of island foxes, and Garcelon et al. (1991) initiated a study to collect data on population densities, home range sizes, habitat use, diet, genetics, and disease. Data collected in 1989-1990 indicated that the population included a large proportion of juveniles compared to age structure observed on other islands, which could indicate high reproductive success and a growing population or relatively higher mortality among the older age classes (Garcelon et al. 1991). Densities on three trapping grids on the East End of the island indicated that fox densities varied across the landscape, possibly due to differences in habitat quality. The three grids differed in fox density, and the density for each grid remained relatively stable during the 2 years (Roemer et al. 1994). The population estimate was 1,342 in 1989-1990 (Roemer et al. 1994).

Limited trapping (76 trap-nights) in 1998 suggested that densities on Catalina Island were much higher than those on the three northern Channel Islands (San Miguel, Santa Rosa, and Santa Cruz) and only slightly lower than on San Nicolas and San Clemente (Roemer 1999). However, surveys conducted in 1999 and 2000 indicated that the fox population experienced a large (possibly >90%) decline apparently due to canine distemper virus (CDV) in 1999 (Timm et al. 2002, Schmidt et al. 2004). Foxes on the east end of the island suffered high mortality, with numbers plunging from an estimated 1,342 in 1989-1990 to an estimated minimum of 28 animals in 2000. Meanwhile, foxes on the west side of the isthmus remained healthy, with no indication of CDV exposure, possibly due to limited fox movement across the isthmus due to high human density at Two Harbors (Timm et al. 2002).

Following this disease outbreak, several recovery activities were implemented. An island-wide trapping program was started to monitor distribution and abundance on the two sides of the island. All captured animals were inoculated against CDV, and a vaccination efficacy study was initiated. In addition, a captive breeding program and facility were established in 2001 (Timm et al. 2002). The captive population was established and augmented with animals from the West End of the island, and offspring from the captive population were released on the East End. In addition, a subset of animals captured on the West End was fitted with radiocollars, released on the East End, and monitored for survival, dispersal, and pair-bonding.

Wild population abundance on Santa Catalina Island did not change noticeably from 2000 to 2002, but the distribution of foxes on the island shifted during this period (Timm et al. 2002, Kohlmann et al. 2003). Animals were translocated from the West End to the East End, West End animals were brought into captivity, and captive-born animals were released onto the East End. The island-wide estimate for 2002 was 215 animals, with 96 and 119 animals estimated in the East and West ends of the island, respectively (Kohlmann et al. 2003). The West End comprises only 16% of the entire island, but supported 56% of all known live foxes on the island (Kohlmann et al. 2003). Kohlmann et al. (2003) reported no differences in reproduction (pups per adult female) between the West End and East End, but age structure in the East End was more skewed toward young age classes, presumably as a result of the 1999 disease outbreak.

A population viability analysis (PVA), conducted with the program VORTEX (Lacey 1993), indicated that the population was still at critically low levels in 2002, with significant risk of extinction, and that a recovery goal of at least 150 animals was needed on each side of the isthmus to minimize extinction risk (Kohlmann et al. 2005). Results of the PVA also suggested that the rate of recovery on the East End of the island depended on translocations from the West End, and that the sustainability of source animals for these translocations depended on the West End supporting at least 150 animals (Kohlmann et al. 2005).

By 2004, field data indicated that the East End subpopulation had reached the desired minimum of 150 foxes recommended by Kohlmann et al. (2003, 2005), and that the West End subpopulation was approaching this goal despite removal of animals for captive breeding and translocation to the East End. The captive breeding program was therefore ended in December 2004, and all captive animals were released into the wild (Schmidt et al. 2005). By 2005, the island-wide estimate was 416 foxes, with 150 and 266 animals estimated on the West and East ends, respectively, and the East End still supporting a much lower density of foxes (1.9 foxes/km^2) than the West End (6.7 foxes/km^2, J. King, SCIC, pers. comm.).

Although Catalina Island foxes have reached the population size targeted by Kohlmann et al. (2003), several factors still threaten population persistence, including disease, feral cats, vehicular trauma, predation, and habitat changes due to invasive species, domestic livestock, and climate change. As demonstrated by the near extirpation of the East End subpopulation, disease risk is a primary threat to all island fox populations, due to small populations, lack of disease resistance, and low genetic diversity (Wayne et al. 1991). Introduction of novel diseases by dogs or other animals brought to the island by humans is a constant and serious risk, with foxes on Santa Catalina Island being at particularly high risk due to the high human population and associated large pet population.

Foxes on Santa Catalina Island have also been afflicted by tumors of the ear canal. The first cases were diagnosed in two foxes trapped during 2000-2001, with increased prevalence observed in 2002 and 2003 (Timm et al. 2002, Kohlmann et al. 2003, Schmidt et al. 2004). The cause of the tumors is not yet understood but may be due to a genetic predisposition or an environmental carcinogen (Kohlmann et al. 2004). Investigations are underway to better understand the etiology of this physical disorder (W. Vickers, IWS, pers. comm.).

Feral cats were trapped during several surveys in the 1970s and, although their abundance, distribution, and relationship to fox population dynamics could not be determined, researchers speculated that feral cats could have negative impacts on the fox population (Propst 1975, Laughrin 1980). In 1987, feral cats were considered one of the major threats to this population

(CDFG 1987). Garcelon et al. (1991) reported that cats were present in high numbers in and around the town of Avalon; they speculated that cats competed with foxes for food sources and could potentially spread pathogens such as *Toxoplasma* to foxes. During the 2000-2001 and 2001-2002 fox trapping efforts, 48 and 49 feral cats were trapped, respectively (Timm et al. 2002, Kohlmann et al. 2003). Timm et al. (2002) suggested that even a slight overlap in diet could cause resource competition between cats and foxes, and that cats could serve as a disease vector. They recommended investigating methods of cat removal. Cats and foxes may also compete for den sites or they could indirectly compete for space (by displacement of foxes; Laughrin 1978). Approximately 700 feral cats currently inhabit Catalina Island (D. Guttilla, CSU Fullerton, pers. comm.). Research is currently being conducted to examine the ecology of feral cats on Catalina Island, including the effect of sterilization on home-range size and distribution (D. Guttilla, CSU Fullerton, pers. comm.).

Collision with motor vehicles also poses a serious threat to Santa Catalina Island foxes, as evidenced by documented mortalities due to vehicular trauma among collared and uncollared foxes (Schmidt et al. (2004). Four of five mortalities discovered in 2003 and at least two of seven carcasses retrieved in 2005 were attributed to car collision, with the majority of cases occurring on the paved road between the summit above Avalon and the airport (J. King, SCIC, pers. comm.). A population viability analysis indicated that viability was sensitive to mortality among all age and sex classes (Kohlmann et al. 2005).

Domestic dogs on Santa Catalina are also a significant threat to island foxes, by increasing the risk of introduced disease and predation on island foxes (Schmidt et al. 2004).

Lastly, grazing by nonnative ungulates has negatively impacted Catalina Island's foxes and may influence their abundance and distribution. Propst (1975) noted that feral pig numbers were high in some parts of the island and may have influenced fox population size and distribution as a result of competition. Although cattle and sheep have been removed from the island, a small number of domestic goats and pigs still persist, along with nonnative bison, mule deer, and blackbuck antelope (Schoenherr et al. 1999; www.catalinaconservancy.org). Although there are hunting and removal programs to control numbers of mule deer and bison, respectively, surveys conducted in 2003-2004 suggested that there could be 1,048 deer and approximately 150-200 bison on the island (Stapp and Guttilla 2006). Grazing by these nonnative species has changed the composition and structure of the island's plant communities (Schoenherr et al. 1999), which has likely altered fox habitat use and possibly increased their risk of predation. In contrast to the northern islands, predation by golden eagles has not been observed on Santa Catalina Island).

6.2 Monitoring Objectives

As described in Section 2.1, the following monitoring objectives were identified for Santa Catalina Island:

Parameters for tracking recovery

- Annual estimate of island-wide population size, with an 80% confidence interval. The point estimate should ideally 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 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.

<u>Parameters for island-specific management decisions</u>

- Cause-specific mortality rates by age and sex, considering all causes of mortality.
- 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.

6.3 Past and Current Monitoring

6.3.1 Summary of Past and Current Protocols

Laughrin (1980) initiated the first quantitative study of island foxes on Santa Catalina Island in 1972 to examine habitat use and relative abundance, diet, and factors affecting population viability. Foxes were trapped in three transects set along roads, each with 10-20 traps spaced at 320-meter (0.2-mile) intervals (Laughrin 1973). Traps were set in coastal sage scrub, woodland, chaparral, and riparian habitats (Laughrin 1980). A measure of trap success was used as a relative index of abundance, and fox density was estimated for each transect by assuming that the transect sampled an area 800 meters (0.5 mile) wide (Laughrin 1973). An attempt was made to extrapolate this value across the entire island 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). While foxes on five of the islands were abundant and widespread, fox abundance on Santa Catalina Island in 1972 was very low, with limited sign observed and only two foxes captured during 60 trap-nights (Laughrin 1973).

Santa Catalina Island was sampled again in 1975, with a more intense trapping effort along approximately 88 kilometers of transects (Propst 1975). Traps were placed in a wide range of vegetation types, excluding sea bluffs, dune grassland, or marine meadow habitat types, with most sampling occurring in coastal sage scrub, the predominant vegetation community on the island (Propst 1975). Traps were set 160-320 meters apart and trapped for 2-3 days (Propst 1975). Results provided a relative index of fox abundance, in the form of trap success, for sampled sections of the island.

During 1988-1991, Garcelon et al. (1991) established three trapping grids on the East End to gather data on density, home ranges, diet, habitat use, genetic variability, and exposure to disease. The original intent was to establish grids in different vegetation types; however, because vegetation communities on Santa Catalina are diverse and interspersed with each other, it was not possible to set a grid in a single homogenous vegetation type. Therefore, each of the three grids (Haypress, Cactus Peak, and Wrigley Ranch) included multiple vegetation types, including grassland, oak woodland, chaparral, coastal sage scrub, and riparian areas (Garcelon et al. 1991, Roemer et al. 1994). Grids included 66 traps (6x11 traps), set 250 meters apart. Trapping duration was 6-7 consecutive nights during May-August in 1989 and 1990 (Garcelon et al. 1991, Roemer et al. 1994). Blood samples were collected for disease, health, and genetic screening (Garcelon et al. 1991). Twelve foxes captured on Haypress were radiocollared to obtain data on home ranges and diel activity patterns (Garcelon et al. 1991). Collared animals were relocated during three daily time periods, and activity was determined by direct visual observation or signal modulation.

Data obtained from this study included trap success, age structure, sex ratios, weights and body condition, and reproductive success (as indexed by the number of females showing signs of lactation or pregnancy). Home range size was estimated for animals with ≥10 locations using the minimum convex polygon method (Mohr 1947). 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), with the latter method included as a comparison method because model selection in the program CAPTURE may not be robust with small sample sizes (Garcelon et al. 1991). 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 (Garcelon et al. 1991). 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, Garcelon et al. 1991). An island-wide population estimate was generated by extrapolating grid-specific density estimates to the entire island. The composition of various vegetation communities (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." Urban, barren, and cultivated areas were omitted from the calculations (Roemer et al. 1994).

In 1998, foxes were trapped along transects on Santa Catalina Island and the five other islands as part of a cross-island comparison of density (Roemer 1999). Traps were set approximately 200 meters apart, for 6 nights, for a total of 76 trap-nights. Trap results were presented as trap success.

After a large population decline due to an outbreak of CDV in 1999, Timm et al. (2002) initiated an intensive trapping program to estimate relative abundance and distribution of foxes and to compare population dynamics on the West and East ends of the island. In addition, data were collected on juvenile dispersal, coarse-scale habitat use, and apparent survival (Timm et al. 2002). Trap transects were located along ridgelines, roads, and trails in an attempt to sample as many parts of the island as possible, with the exception of rugged and steep areas (Timm et al. 2002). Trap spacing averaged 320 meters on the West End of the island, with larger and variable inter-trap distances on the East End, where fox density was low after the 1999 population decline. Blood samples were collected for disease screening as part of a CDV vaccination efficacy study (Timm et al. 2002).

As part of a translocation study investigating the effectiveness of translocating young foxes from the West End to the East End, the survival of 20 collared foxes was also monitored via radio telemetry. The study group comprised ten translocated animals and ten non-translocated animals. Collars were equipped with mortality sensors, and signals were monitored at least three times a week for the first month and then once weekly to assess survival and general locations for 1 year (Timm et al. 2002). A subset of foxes included in the CDV vaccination efficacy study on the West End was also collared and monitored for survival (Timm et al. 2002).

This trapping effort, conducted at various times of the year from September 24, 2000 through October 3, 2001, provided data on sex ratios, age structure, relative indices of density for the West and East ends of the island (in the form of trap success), an index of reproduction (number of fox pups captured), general locations of translocated individuals, general health and condition of captured foxes, including CDV titers, and survival data on a subset of the animals (Timm et al. 2002). Minimum island-wide abundance estimates were generated based on a minimum number of animals known to be alive during the trapping period; however, Timm et al. (2002) suggested that this estimate may be biased, as habitat quality and fox density varied across the island.

During 2002-2006, fox research on Catalina Island generally followed the above methods to monitor the relative abundance and distribution of foxes on the West and East ends of the island, track survival and cause-specific mortality of animals translocated from the West End to the East End (in 2002), and track the health and survival of individuals included in vaccine efficacy studies (Kohlmann et al. 2003, Schmidt et al. 2004, J. King, SCIC, pers. comm.). Approximately 605 traps were set along transects of 55 traps each, for a total of 2,420 trap-nights (J. King, SCIC, pers. comm.). Inter-trap distance varied slightly between years (Kohlmann et al. 2003), with an average inter-trap distance of approximately 250 meters in 2005 (J. King, SCIC, pers. comm.). Additional focused trapping was conducted as needed, to replace collars or to check on an animal's health (Kohlmann et al. 2003, Schmidt et al. 2004). As part of ongoing health monitoring and the CDV vaccination efficacy study, animals were vaccinated, blood samples were collected from all captured individuals, and feces were collected from trap boxes (Kohlmann et al. 2003). In addition, a study on ear-tumors has been conducted during recent years (and is continuing today), and all foxes found dead have been submitted for pathology at UC Davis (Schmidt et al. 2004, W. Vickers, IWS, pers. comm.).

In 2002, 41 animals were monitored on the East End. Twelve of these had been translocated from the West End to the East End, and the remainder were animals released the previous year (Kohlmann et al. 2003). Signals were monitored daily for 1 month after release, and then weekly thereafter. Signals were monitored via ground or aerial telemetry. Exact fox locations were obtained during ground tracking, and approximate locations were obtained via triangulation in other cases (Kohlmann et al. 2003). In 2003, no animals were translocated, but 57 collared foxes (>20% of the wild population) were monitored for survival, cause-specific mortality, and general space use (Schmidt et al. 2004). Capture histories on 188 individually-identified foxes were used to estimate survival, using known fate models in program MARK (Kohlmann et al. 2003).

Trap success was used as an index of abundance among parts of the island, and MNKA was calculated (Kohlmann et al. 2003, Schmidt et al. 2004, J. King, SCIC, pers. comm.). Assuming an effective trap radius of 500 meters around each trap, 79% and 70% of the West End and East

End, respectively, were sampled (Kohlmann et al. 2003, Schmidt et al. 2004). This estimate was used in combination with the MNKA to generate an island-wide population estimate. The 500-meter radius was based on approximate home range size for foxes on San Clemente Island and translocated foxes on Santa Catalina Island (Schmidt et al. 2004). In addition, a 1-km^2 grid was overlaid over the island and, based on the number of individual foxes captured in each grid cell, a mean and standard deviation of fox density was generated (foxes per km^2), which were used to extrapolate over unsampled areas. Population size was estimated by adding the number of foxes trapped (MNKA) to the number estimated as being in the unsampled areas (Schmidt et al. 2004).

6.3.2 Representation Analysis of Current Trapping Protocols

To determine how well existing trapping layouts sample habitat variability on the East and West ends of the island, we conducted univariate and multivariate representation analyses (Appendices C and H). The current trapping effort samples approximately 79% and 84% of the East and West ends, respectively, assuming a 600-meter effective trap radius.

Trapped areas (specific to either the East or West ends) differ statistically in slope, ruggedness, distance to the shoreline, and vegetation (Maps 6-2, 6-3, and 6-4) from the island as a whole. In addition, they differ in distance to freshwater on the East End and in distance to developed areas on the West End. Although statistically significant, it is not known if these differences are biologically significant or would influence accuracy of trapping analyses, as some differences are small relative to documented fox movement patterns (e.g., distance to freshwater or to developed areas) or seem irrelevant given the small absolute difference (e.g., slope and ruggedness; Appendix C). Although there was a statistically significant difference in vegetation composition between trapped and island-wide areas, vegetation representation is relatively good, in particular on the East End (Appendix C). The greatest bias on both ends of the island may be caused by under-representation of areas near the shoreline.

Mean principal component (PC) scores for trapped areas also differ from those for the entire island. On the East End, current trapping locations under-represent dry, remote, steep shoreline and modestly over-represent remote and gentle terrain. All other habitat types are well-represented by current trapping. While the transects sample vegetation types in rough proportion to their occurrence, trap locations within each vegetation type under-sample steep shoreline, favoring locations with gentler terrain that is closer to interior lands and development than random points.

On Santa Catalina Island's West End, transect trapping under-represents steep and remote habitat and modestly over-represents interior habitat and habitat close to development. Existing transects sample vegetation types in rough proportion to their occurrence. Trapping in both grassland and chaparral vegetation types is representative of island-wide habitat characteristics. In the remaining vegetation types, trapping locations are biased in their habitat characteristics consistent with overall patterns of bias.

6.3.3 The Ability of Existing Protocols to Meet Current Objectives

This section discusses the adequacy of existing protocols to address current monitoring objectives (Section 6.2). We recognize that previous 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

Although past field data have been used to generate an island-wide population estimate, several shortcomings limit the accuracy and precision of these estimates:

1. Current trapping is along transects which can provide relative abundance indices in the form of trap success. However, transect sampling typically is not used to generate density estimates using traditional mark-recapture analysis methods and, in general, data from transect sampling do not provide estimates of abundance or density as precisely as grid trapping data. A primary shortcoming of transect trapping is the difficulty of estimating effective trap area around the transect (Spencer et al. 2006, Schmidt and Garcelon 2003). However, we recognize the challenge of trapping grids on steep and rugged terrain, and suggest that transect sampling may be necessary. Fortunately, newly developed methods of spatially explicit capture-recapture analysis (Efford 2004) should allow use of modified transect configuration on large rugged islands (Section 6.4.2).
2. Grids trapped during 1989-1999 would likely also provide an inadequate estimate for the entire island. Because each grid represented several different combinations of vegetation communities, and collectively the three grids did not adequately represent vegetation variability on the island, extrapolation to the remainder of the island is problematic.
3. The use of a 1-km^2 grid overlaid on the island to extrapolate density to unsampled parts of the island may be problematic. It is not clear if this approach corrects data for capture effort per grid cell. That is, a cell including several traps might be weighted the same as a cell with only one trap. This approach also appears to assume that all foxes present in the cell would be captured rather than accounting for capture probabilities using traditional mark-recapture methods. This method, as currently used, does not take into account different densities in different habitat and does not include a way of estimating sampling error. These shortcomings were also recognized by Kohlmann et al. (2003).
4. Current transect trapping may be biased in terms of representation of some habitat types on the island. For example, the existing protocol tends to under-sample areas near the shoreline (Appendices C and H). This may be the case for any feasible trapping protocol, because shoreline areas may be too steep and rugged to safely trap. We therefore suggest that research on habitat use and selection be conducted to better understand whether over- or under-sampling certain habitat types may bias density estimates.
5. The current trapping protocol is labor-intensive and costly, approaching an island census rather than an estimate based on sampling methods. Kohlmann et al. (2003) suggested that randomized sampling, stratified by habitat types and possibly using mark-recapture techniques, would be more efficient and robust.

Survival and cause-specific mortality rates

Although annual capture data on marked animals can be used to estimate apparent survival rates, they don't reveal mortality causes or distinguish emigration from death, and they do not facilitate immediate management response in the event of a disease outbreak or sudden increase in other forms of mortality. Tracking radiocollared foxes can help rectify these shortcomings, but several factors may limit the ability to generate robust estimates of survival and cause-specific mortality using previous methods:

1. The time period for tracking may be inadequate. Garcelon et al. (1991) tracked a small number of radiocollared animals, but the transmitters had a limited life-expectancy (8-9 months). Unless foxes are recaptured to replace collars, or battery life of collars is extended, incomplete information on survival patterns results.
2. Small sample sizes of collared and monitored animals do not provide adequate surveillance for disease. Timm et al. (2002) suggested that sample sizes may have been too small to detect diseases or to adequately represent incidences of road kills. Kohlmann et al. (2003) also commented that sample sizes (at that time representing about 18% of the population) may be a limiting factor. We suggest, however, that 18% could be adequate, depending on the absolute number of collared animals, how collared animals are geographically distributed, and the intensity of monitoring.
3. Radiocollared foxes may not be representative of the entire population. Garcelon et al. (1991) radiotracked foxes from only one grid (Haypress), which may not have represented island-wide survival patterns. Many of the collared animals monitored after the 1999 disease outbreak were foxes translocated or released from captivity, rather than a random sample of the population (Kohlmann et al. 2003). In addition, many radiocollared animals were captured along road transects, which could have biased estimates of survival and mortality rates if animals living near roads had a higher probability of being hit by a car. Finally, reflective tape was applied to collars after the disease outbreak, which could affect predation rates or chances of being hit by a vehicle, thus biasing estimates of cause-specific mortality.
4. Radiocollaring and monitoring animals on Santa Catalina Island has not been continuous, so there are no long-term data on survival to allow for yearly comparisons. To satisfy current monitoring objectives, radiocollared animals should be monitored continuously during all times of the year.
5. Survival monitoring may not be frequent enough to determine causes of death. Kohlmann et al. (2003) noted that it was difficult to monitor collared foxes once per week, due to limited resources (personnel hours and/or vehicles), other field responsibilities, and difficult access in parts of the island. Pathologists recommend that animals be checked multiple times per week to increase the chance of recovering carcasses before decomposition, to allow meaningful necropsy results.

Trends in population abundance or density

The extensive transect trapping that occurs every year on Santa Catalina Island may provide a useful index of changes in density. It is even possible that a less intensive effort could provide such an index, with trap success providing an index of relative abundance over time. However, several aspects of the trapping protocols must be standardized to make year-to-year data comparable:

1. Trap success alone should not generally be used as an index but instead should be corrected for capture probability.
2. The location and spacing of traps have not been standardized across all years. For example, in past years, trap spacing averaged 320 meters on the West End but was more variable and larger on the East End (Timm et al. 2002, Kohlmann et al. 2003), while inter-trap distances on the West End changed from 320 meters in 2000-2001 to 250 meters in 2002. Most reports (e.g., Schmidt et al. 2004) do not show trap locations, but changes in inter-trap distances suggest that trap locations were altered between years. Standardized transects should be trapped at the same locations every year, with the same inter-trap distances, because inter-trap spacing can influence capture probabilities.
3. It is not known if transacts are trapped according to a standardized schedule during the annual trapping period. Transects should be trapped at the same time every year and, ideally, the trapping period should be standardized among islands.
4. It is not known if all protocols, such as the time of day traps are opened, checked, and closed, types of bait, and types of traps, have been kept constant across years. Protocols should remain constant as much as feasible to reduce confounding factors in trend data.
5. Sampling is not distributed across the island to represent all habitat types and geographic areas. We recognize that this will likely be impossible with any feasible trapping protocol, due to Santa Catalina Island's rugged and steep terrain. We therefore suggest that (a) an attempt is made to distribute trapping across the island, whether by random or stratified placement, and (b) habitat use and selection studies be conducted to determine if under- or over-representation of certain habitat types introduces biases into trend analysis (see Section 6.5.3).

6.4 Monitoring Protocols for Santa Catalina Island

6.4.1 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 Santa Catalina Island must consider the following specific issues:

1. The island contains extensive areas of rugged and steep terrain, which make fieldwork, especially trapping, hazardous to personnel and foxes (Maps 6-3 and 6-4). Approximately 54% and 74% of the East End and West End, respectively, has terrain with slopes greater than 30% (16.7°), which, according to NPS management, is the maximum steepness feasible for field work.
2. Although there is a fairly extensive system of roads and trails, the island's large size constrains some monitoring activities, such as daily signal checks from the ground.

3. Large numbers of visitors are present during some seasons, and it is not possible to safely set traps in areas of high public use.

6.4.2 Candidate Trapping Protocols

There are two options for trapping protocols on Santa Catalina Island (Section 2.4.1): island-wide random trapping and transect-based trapping using multiple small trapping units.

We first evaluated the feasibility of island-wide random trapping. Although we did not specifically analyze this method on Santa Catalina Island, analyses conducted on San Miguel, San Nicolas (Appendices K and L), and Santa Cruz (data not shown) suggested that this method would not be feasible on the three larger islands (Santa Catalina, Santa Rosa, Santa Cruz).

We therefore explored the use of transects, which are more practical in rugged and steep terrain than grids (Appendix M). Simulation results indicate that parallel paired lines (referred to here as *units*) produce better results than single straight lines with the same number of traps and spacing. Therefore, 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 (Appendix M). Given a particular trap layout and duration, 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 at a range of densities, and detection parameters were set at a range of plausible values as well as a best estimate of detection scenarios, generated by V. Bakker 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.

Simulation results suggest that 33 recaptures would be necessary to obtain a mean $CV(\hat{D})$ = 20%, and that 40 recaptures would further assure that this precision was obtained in most runs (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 $CV(\hat{D}) \leq 20\%$. Our goal was to identify logistically feasible scenarios that would obtain at least 33 recaptures and, based on number of expected recaptures, we estimated expected precision with the equation $CV(\hat{D}) = 0.894m^{-0.297}-0.116$, where m = the number of recaptures (Appendix M).

Simulation results suggested that adequate precision ($CV(\hat{D}) \leq 20\%$) could be obtained at current densities (West End and East End estimates of 6.7 and 1.9 foxes/km^2, respectively) if a total of 22 units were trapped, with six on the West End and 16 on the East End. If densities on the West and East ends fall to 2.0 and 1.0 foxes/km^2, respectively, precision of the density estimate would likely decrease, with $CV(\hat{D})$ on the West End likely increasing to over 25% and $CV(\hat{D})$ on the

East End increasing to approximately 25%. We propose this scenario as Santa Catalina Island Trapping Scenario A. We produced a suggested map of this scenario by placing (and orienting) the 22 units randomly on the island, with the following rules: (a) Units must originate on or near a road, (b) units must be ≥1,500 meters apart to reduce the chance of an individual fox moving between grids, (c) units could not be placed in areas of high human activity such as popular bays and campgrounds, or on leased lands, and (d) trap locations should avoid steep slopes [i.e., ≥30% (16.7°) slope] to reduce risks to field personnel (Map 6-5). Although it is possible to place units closer to each other, 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.

If densities decrease and remain at low numbers, it would be desirable to have more trap units to maintain adequate precision. We therefore increased the number of units on the East End to 20 units. However, it was difficult to place more than six random units on the West End, due to its small size, subject to the inter-unit distance constraints. The resulting scenario (6 units on the West End and 20 on the East End) will therefore provide a higher precision (CV($\hat{D}$) = 22%) on the East End if density were to fall to 1.0 fox/km^2. We propose this scenario as Santa Catalina Island Trapping Scenario B (Map 6-6), with units located in the same manner as for Scenario A.

There is no correct answer on scenario choice, and variations of the two scenarios defined above are possible. The final choice will depend on the trade-off between effort expended and desired precision, which will depend in part on population density and recapture rates. At current densities, Scenario A with 1,584 total trap-nights will provide good precision. Although the total number of trap-nights in Scenario A is lower than in the existing protocol (2,420 trap-nights), some units may require increased effort because some traps will now be farther from the road. If this level of effort is deemed impractical, random units could be eliminated to reduce effort, but with reduced precision. For example, if the number of units on the East End were reduced from 16 to 12, a density estimate with a CV of approximately 24% would result for that end of the island, at current fox densities (Appendix M). We developed Scenario B, with a total of 1,872 trap-nights, as an option that would provide more precise estimates if population density decreased. In that respect, Scenario B provides more flexibility for a range of densities.

The expected precision of any of these three scenarios could 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.).

6.4.3 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 the two candidate protocols (Scenarios A and B) to habitat variability in island-wide areas and those sampled by existing protocols (Appendices C and H).

Univariate analyses (Appendix C) indicate that, in general, existing protocols sample habitat variability on the island more effectively than Scenario A and B, no doubt due to the larger proportion of the island sampled. Scenarios A and B sample only 28% and 35% of the East End, respectively, while each samples 50% of the West End. In contrast, existing protocols sample about 79% and 84% of the East and West ends, respectively, if a 600-meter effective trap radius is assumed (Appendix C). Univariate analyses suggest that Trapping Scenario B tends to sample the island more adequately than Scenario A. Statistically, areas sampled by all three trapping scenarios (including existing protocols) differ from random points on the island for all habitat measures examined, with the exception of distance to paved roads and developed areas on the East End of the island under existing trap protocols. However, as discussed in Appendix C, statistical differences may not indicate biologically relevant differences. For example, statistical differences were found in slope and ruggedness, but absolute differences were small and may not influence trapping results. However, under-sampling of some areas, such as areas close to the shore, may bias trapping results if fox density is different close to the shore than in other areas. Increasing sampling in some areas, such as close to the shore, will remain problematic, however, due to logistic and safety issues, and this will likely mean that any logistically feasible protocol will also sample areas that area less steep and less rugged than island-wide areas.

Multivariate analyses (Appendix H) indicate that, on the East End of the island, both existing and proposed trapping scenarios under-sample the island's steep escarpment far from development. Proposed scenarios also significantly over-sample areas far from paved roads and development, regardless of slope and ruggedness. Scenario A represents the multivariate attributes of the island modestly better than Scenario B. On the West End of the island, existing and proposed trapping scenarios again under-sample steep terrain far from development, with the proposed scenario more substantially biased in this regard. Existing transects over-sample rugged interior habitat, while the proposed scenarios over-sample gentle remote interior. 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.

We suggest that future research be focused on fox habitat use and selection to test whether under- or over-sampling certain habitat characteristics is expected to bias trapping results. Density and demographic rates in disproportionately-sampled habitat types should be compared to overall island-wide patterns to ensure that monitoring program results are not biased.

6.4.4 Survival and Cause-Specific Mortality Monitoring

Due to the large size and rugged terrain of Santa Catalina Island, frequent ground monitoring of signals will be difficult, even if a full-time person and vehicle were dedicated to the task. Currently, signals from 30-60 foxes are checked from the air by a volunteer pilot once per week. The use of remote telemetry receivers could be considered as an alternative or an addition to ground monitoring on this island (see Section 2.4.2). However, assuming a detection range (the distance over which a collar signal can be detected assuming a line-of-sight signal) of 5 km, many tall towers would likely be necessary to monitor all of Santa Catalina Island. A preliminary viewshed analysis suggested that nine 45-meter high towers with a 5-km detection range would not adequately monitor San Clemente Island, which is smaller and has less rugged terrain than Santa Catalina Island. A viewshed analysis would be needed to determine the necessary number and most effective placement of towers, based on their height, and to determine portions of the island that would be monitored effectively by the remote system. Prior to the viewshed analysis, the detection range of collars should be confirmed in the field.

We believe the most promising approach for monitoring radiocollared foxes on Santa Catalina Island would be continued aerial monitoring. However, the frequency of flights would need to be increased, ideally to a flight every other day, if not every day. Ideally, a pilot and airplane should be contracted for a regular pre-determined schedule of flights, barring any mechanical or weather-related problems. As described in Section 2.4.2, aerial monitoring may be the most effective strategy on the three largest islands (Santa Catalina, Santa Rosa, and Santa Cruz) and an option that should be explored is the idea of the three island managers (SCIC, NPS, and TNC) jointly contracting a pilot and airplane to monitor the islands on a regular basis. This may reduce the collective cost of monitoring foxes on these islands and provide a thorough and efficient means of checking signals on Santa Catalina Island.

If frequent aerial monitoring is deemed infeasible, the use of GPS collars or a combination of ground monitoring and remote telemetry monitoring should be considered (Section 2.4.2). For the latter, personnel hours should be dedicated for regular monitoring of areas accessible by existing roads and trails, and remote monitoring towers could be placed strategically to detect signals in areas difficult to access from the ground. For example, a viewshed analysis could identify all areas that could be monitored from existing roads and trails on a regular basis. Placement of remote towers could then be evaluated to detect signals from the remaining parts of the islands. For example, towers could be placed on high points above deep canyons or above cliffs along the shoreline. If field personnel are unable to check the entire island frequently enough, on-the-ground monitoring efforts can be split geographically so that half the island is checked one day and the other half is checked on alternating days. We suggest that survival estimation be performed with the known fate model in program MARK.

6.5 A Tiered Approach for Population Monitoring

6.5.1 Recommended Long-Term Trapping Protocols

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

- Scenario A: 22 units of 2x6 traps, trapped for 6 nights, for a total of 1,584 trap-nights annually (Map 6-5)
- Scenario B: 26 units of 2x6 traps, trapped for 6 nights, for a total of 1,872 trap-nights annually (Map 6-6)

Trapping should be conducted at the same time each year and synchronized with timing on other islands to facilitate the most accurate comparisons across years and islands. We suggest that July represents the 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.

6.5.2 Recommended Monitoring for Survival and Cause-Specific Monitoring

To address a primary monitoring objective outlined in Section 2.4, and to track survival and cause-specific mortality for Santa Catalina Island foxes, the following actions are recommended:

1. Annually radio-collar at least 40 foxes with mortality-sensing collars (Section 2.4.2). These foxes should be widely distributed across the island. 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 composition or numbers of 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. Explore the option of aerial signal monitoring, ideally in collaboration with monitoring efforts on Santa Rosa and Santa Cruz islands. If feasible, contract pilot and airplane to conduct routine (ideally daily, but at least every other day during summer) monitoring of all radiocollared foxes.
3. If aerial monitoring is not feasible, explore the option of a remote monitoring system to augment ground monitoring.
    - 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 identify areas that can be monitored from the ground via telemetry from established roads and trails.
    - Conduct a viewshed analysis to determine number and locations of towers necessary to monitor animals in areas where ground-monitoring is not feasible. 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).
    - Dedicate personnel hours needed to assure that signals are checked in all the ground-monitoring areas at a minimum of 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.
    - If the above investigations warrant the use of remote telemetry on towers, construct towers and install and test the automatic recording system.
4. Explore using GPS collars to monitor animals for survival (Section 2.4.2).
5. Have personnel on call on the island to immediately locate and investigate mortalities, and develop a protocol for transporting carcasses to UC Davis for necropsy.

6.5.3 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 Santa Catalina Island include:

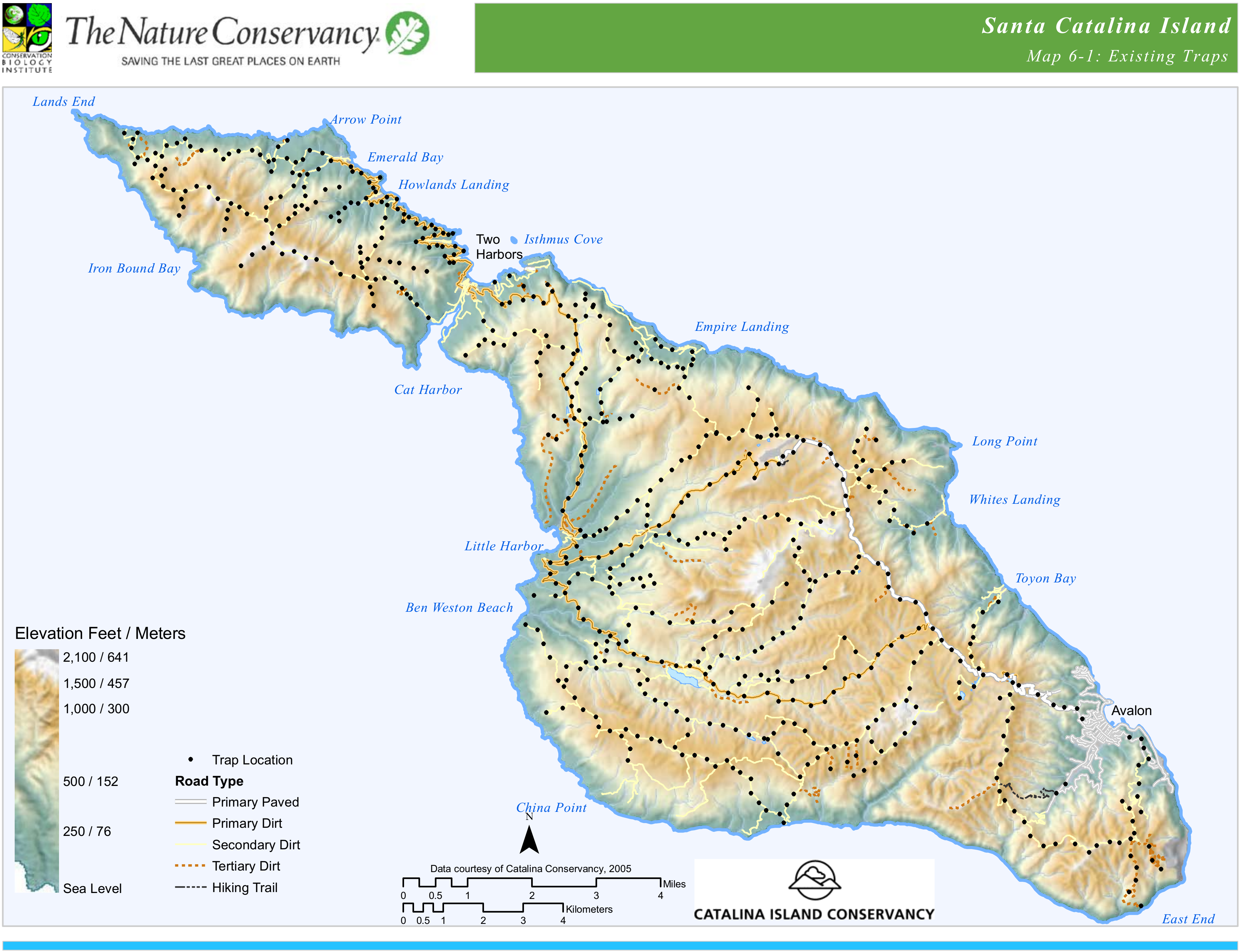
1. Habitat and space use**.** Habitat selection and space use studies should examine behavioral and demographic patterns relative to roads, human activity, vegetation types, water sources, shoreline areas, and cat densities. These data will be useful in interpreting annual trap data (e.g., to determine if over- or under-representation of certain habitats or portions of the island are likely to bias population estimates up or down). In addition, studies of home range size and movement patterns will increase our understanding of habitat quality differences which could lead to source-sink dynamics. Kohlmann et al. (2003) reported that foxes on Santa Catalina Island appeared to be aggregated in some areas, suggesting differing habitat quality across the island. These authors also recommended that further habitat-specific studies examine reproduction, survival, movement, and the potential of source-sink dynamics. Studies to quantify the degree of movement between the West and East ends of the island may provide valuable information on the pros and cons of a distribution barrier. The presence of radiocollared animals (for survival monitoring) will greatly facilitate such studies.
2. Disease and health**.** Although standardized disease and health monitoring will be conducted every year, 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. For example, on Santa Catalina Island, studies should be continued on the etiology and health impacts of ear tumors.
3. Ecological relationships with feral cats. Cat density and distribution may influence the viability, abundance, and distribution of island foxes, and previous studies have suggested an inverse relationship between densities of foxes and cats (Kovach and Dow 1981, 1986). Continued studies could provide information on competition (e.g., for prey, den sites) and how interactions between the two species vary across seasons, years, and population densities.
4. Human perspectives and education. A survey should evaluate visitor and resident knowledge about foxes and the proportion of visitors (including those arriving by private boat) bringing dogs to the island. This information can help design the most effective educational programs, aimed primarily at reducing risk to foxes from transport of unvaccinated dogs, feeding of foxes, excessive speeds on roads, and use of rodenticides.
5. Reproduction and early pup survival. Although annual trap data may provide some information on reproduction (e.g., indexed by the proportion of captured females exhibiting signs of reproduction), further research is needed on reproduction, early 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 (via scat or hair sampling) may be necessary.

6. Traffic. Temporal and spatial patterns of traffic volume and velocity, when paired with data on spatial and temporal patterns of road kills and island fox movement in relation to roads and other habitat features, will help identify management alternatives. For example, if road kills tend to be more frequent during one season of the year, such data would help discern whether this increase is due to changes in traffic volume or velocity vs. changes in fox movement patterns.
7. Vegetation. The island-wide vegetation map should be updated every 5-10 years. As part of this effort, field work should be conducted to measure vegetation height, structure, and composition at pre-determined sites to track changes due to habitat recovery, climate change, and human activity. These data will be useful for understanding temporal and spatial patterns of fox habitat use. The relative isolation of the West End of the island allows for different management of pest plants and animals, and so may serve as an interesting *treatment* to explore various aspects of fox community dynamics.
8. Rodenticide use. An island-wide survey of rodenticide should determine the types, amounts, and dispersal device being used on the island. In addition, all dead foxes, whether suspected of dying from rodenticide poisoning or not (e.g., road-killed individuals), should be tested for rodenticide levels. This information should be stored in one comprehensive file available to veterinarians monitoring island fox health.
9. Effectiveness of remote telemetry stations. If aerial monitoring of fox survival is not feasible for the long-term, a study should explore the use of remote monitoring systems to augment survival monitoring efforts on the ground. This should include determining 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 6.5.2).
10. 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.
11. 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 additional non-fox data that should be routinely monitored and integrated with fox data.


The Nature Conservancy
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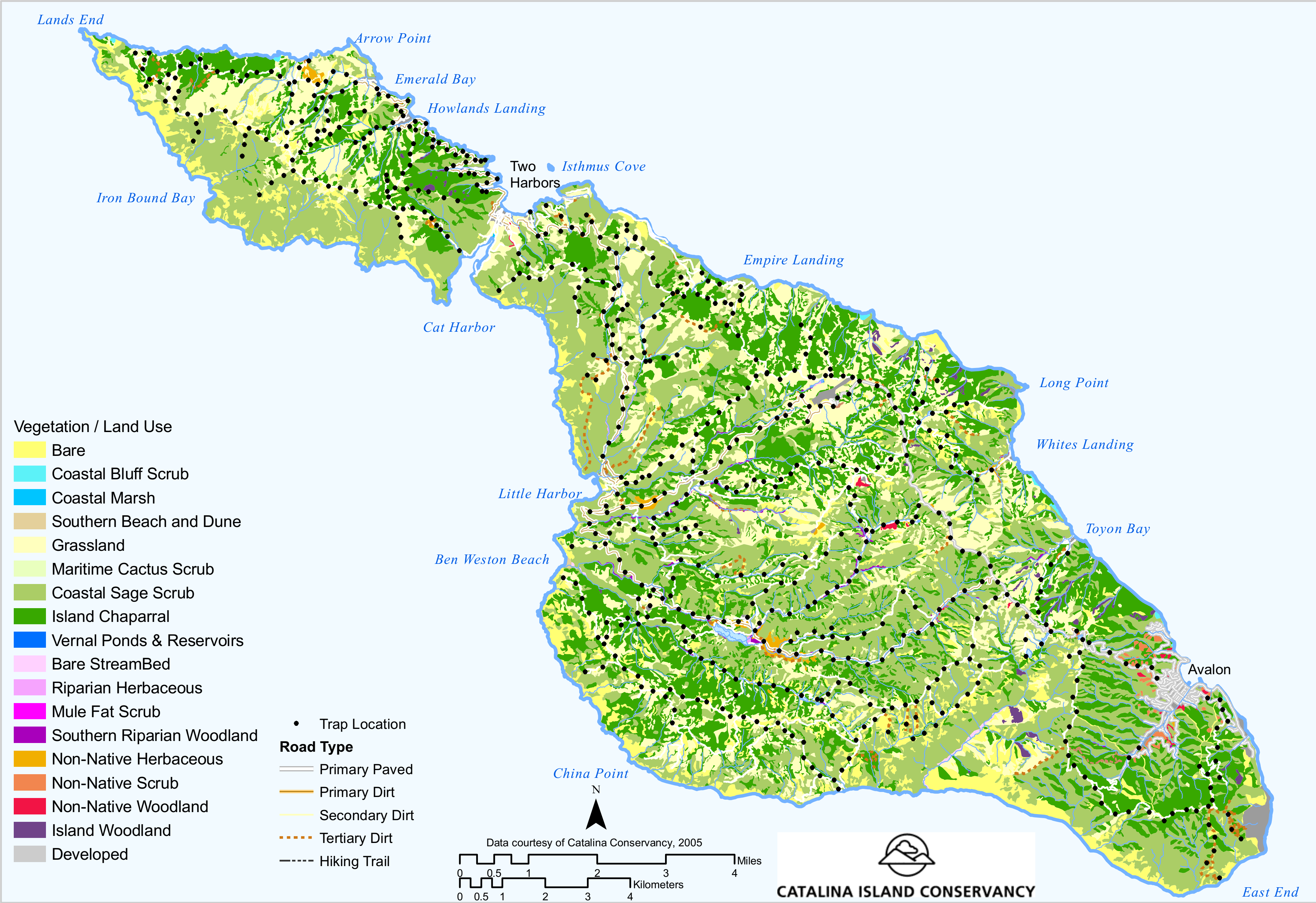
CONSERVATION BIOLOGY INSTITUTE
Santa Catalina Island
Map 6-1: Existing Traps
Lands End
Arrow Point
Emerald Bay
Howlands Landing
Two Harbors
Isthmus Cove
Iron Bound Bay
Empire Landing
Cat Harbor
Long Point
Whites Landing
Little Harbor
Toyon Bay
Ben Weston Beach
Avalon
China Point
East End
Elevation Feet / Meters
2,100 / 641
1,500 / 457
1,000 / 300
500 / 152
250 / 76
Sea Level
Trap Location
Road Type
Primary Paved
Primary Dirt
Secondary Dirt
Tertiary Dirt
Hiking Trail
N
Data courtesy of Catalina Conservancy, 2005
0 0.5 1 2 3 4 Miles
0 0.5 1 2 3 4 Kilometers
CATALINA ISLAND CONSERVANCY

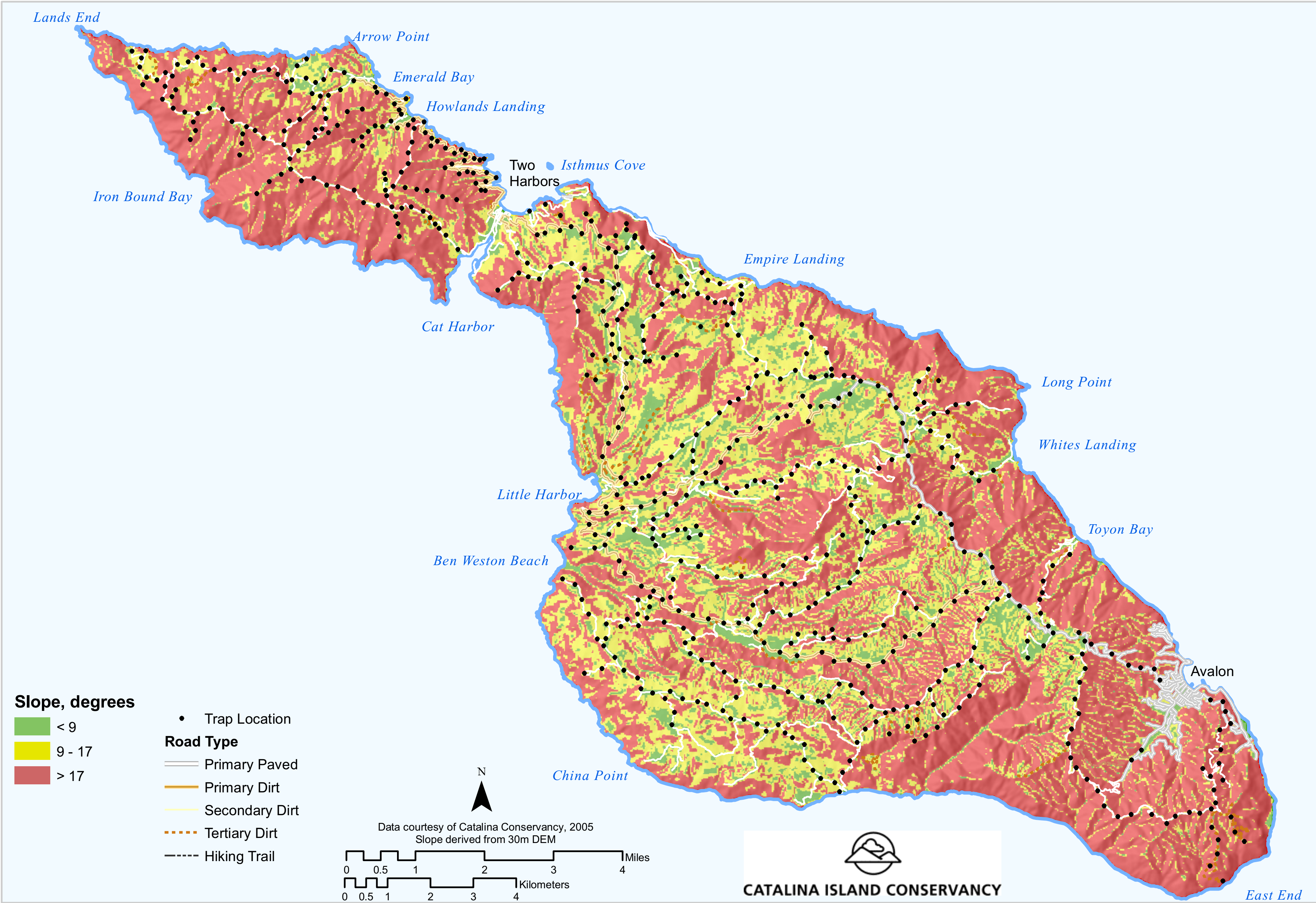
Santa Catalina Island

Map 6-2: Existing Traps in Relation to Vegetation



Santa Catalina Island

Map 6-3: Existing Traps in Relation to Slope



Santa Catalina Island

Map 6-4: Existing Traps in Relation to Ruggedness

Data courtesy of Catalina Conservancy, 2005
Ruggedness derived from 30m DEM

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

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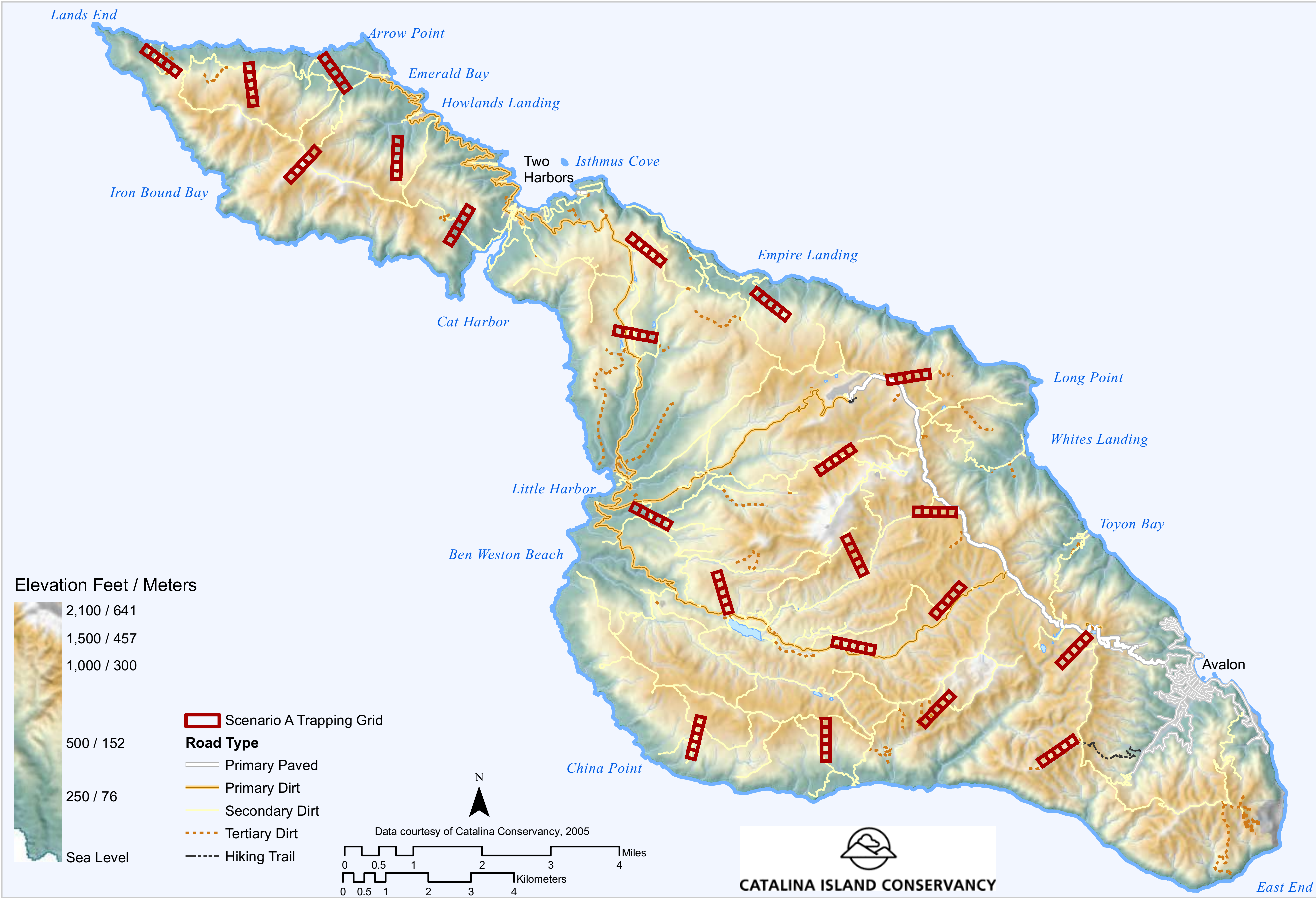
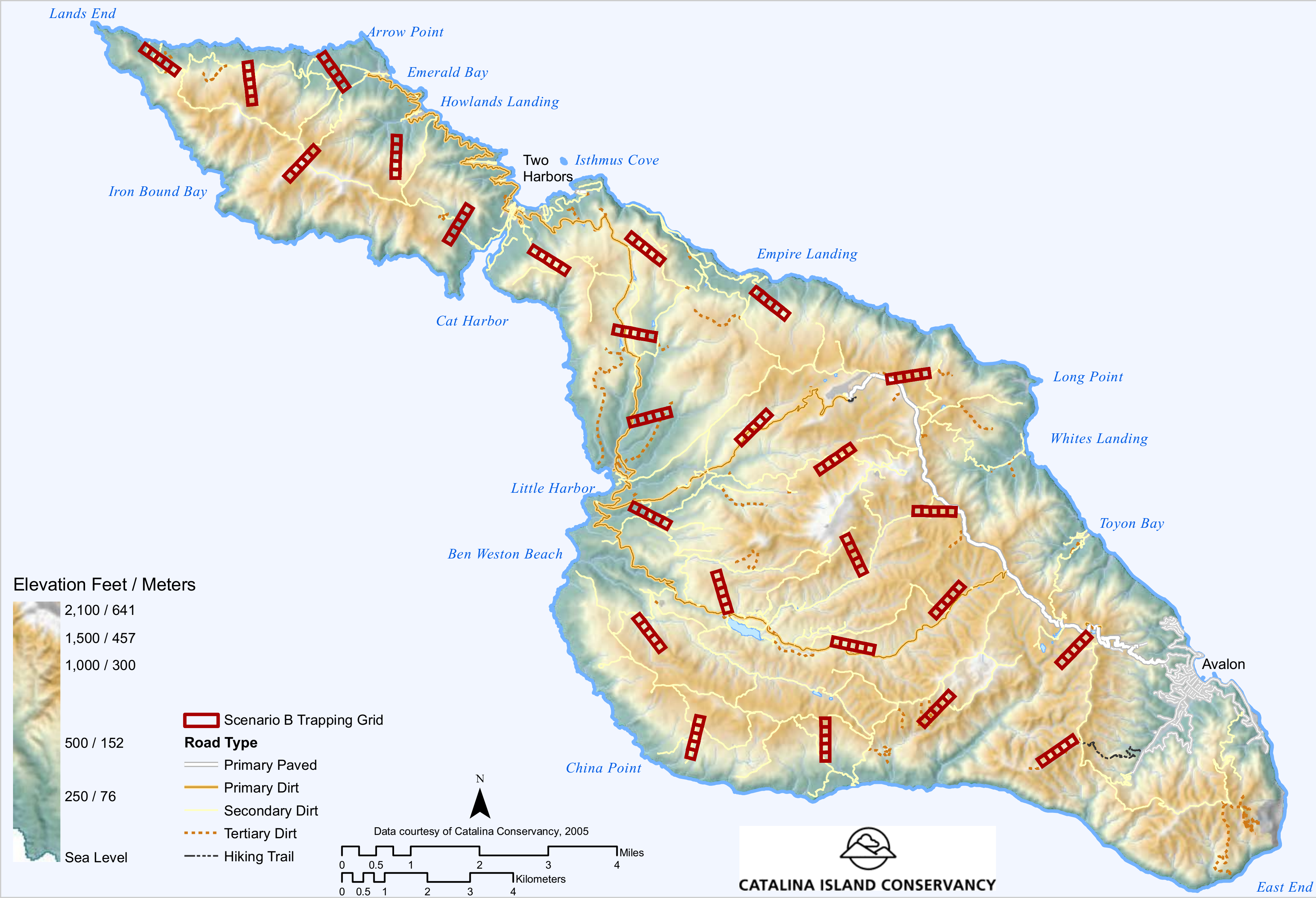
Santa Catalina Island

Map 6-5: Trapping Scenario A



Santa Catalina Island

Map 6-6: Trapping Scenario B



7 A Monitoring Plan for Santa Rosa Island Foxes

Santa Rosa Island, with an area of 218 km^2, is the second largest of the Channel Islands (Table 1-1; Map 1-1). The island is located 44 km from the mainland and measures about 16 by 24 km (10 by 15 miles) in dimension (Schoenherr et al. 1999). Santa Rosa Island is located between San Miguel and Santa Cruz islands, and its topography is intermediate between the topography of these two islands. On its western side the island tends to resemble San Miguel Island, with more gentle topography and more sandy terrain, while further east the island has more diverse habitat, with deep-cut canyons and several relatively-rounded peaks that reach 508 meters (1,574 feet) at Soledad Peak (Schoenherr et al. 1999; Map 7-1). The island was privately owned until 1986, when it was purchased by NPS.

This large island supports at least 31 species of breeding birds, but is home to only four species of native mammals, including the island fox, the Santa Rosa Island deer mouse (*Peromyscus maniculatus sanctaerosae*), the island spotted skunk (*Spilogale gracilis amphialus*), and the California bat (*Myotis californicus*; Laughrin 1973, Schoenherr et al. 1999). Santa Rosa Island supports a high diversity of vegetation, with up to 380 species of plants collected on the island, and at least three species endemic to the island. However, the island is mostly grassland (70% of the island area) and coastal sage scrub (17% of the island), with the remaining 16 vegetation associations found in small scattered patches (Map 7-2). Perennial shrubs, such as sagebrush (*Artemisia* spp.), coyote bush (*Baccharis* spp.), island oak (*Quercus tomentella*), scrub oak (*Q. dumosa*), and toyon (*Heteromeles arbutifolia*) are found primarily in gullies and canyons that cut through the grasslands (Laughrin 1973). It is likely that vegetation composition is a result of intensive grazing and that grasslands were once less widespread (Schoenherr et al. 1999). The island has several freshwater sources, including seeps and springs (Laughrin 1973).

7.1 Santa Rosa Island Foxes

Foxes on Santa Rosa Island were first described by C. H. Merriam in 1903 (Laughrin 1971). Anecdotal observations suggest that foxes on Santa Rosa Island, as on other islands, have experienced fluctuations in abundance prior to 1972 (Laughrin 1973, 1980). The first quantitative surveys were conducted in 1972, at which time the fox population appeared healthy, widespread, and relatively abundant (Laughrin 1973). Laughrin (1973) noted that fox densities were higher in areas of increased plant diversity and structure, as in shrub and mixed habitats, versus more open grassland habitats.

There were very few field studies on Santa Rosa Island foxes between the early 1970s and the late 1990s. Based on extrapolations of fox densities on San Miguel and Santa Cruz islands, Roemer et al. (1994) estimated that there may have been 1,780 foxes on Santa Rosa Island in 1994. During mid- to late-1990s, however, the population experienced a precipitous decline, with very few foxes captured during 1998-2000 (Roemer 1999, Coonan 2003). By the end of this decline, only 14 foxes remained. These were brought into a captive breeding facility established in 2000 in response to the population decline (Coonan 2003, Coonan et al. 2004).

Predation by golden eagles was determined to be the cause of this decline (Roemer 1999). It is believed that golden eagles first colonized the northern Channel Islands in the early 1990s, with the first reported sightings in 1993 (Roemer 1999, Roemer et al. 2001b). During that year, an eagle roost site with fox remains was found on Santa Rosa Island (Roemer 1999). Golden eagle sightings increased in the northern islands during 1993-1998, as did predation by golden eagles, with low fox survival rates leading to near extirpation of the wild population on the three northern islands (Roemer 1999, Roemer et al. 2001b). Eagle predation and associated fox population declines were documented on San Miguel and Santa Cruz islands (Roemer 1999). During this period, fox captures and density estimates on two capture grids on Santa Cruz Island decreased, and it was estimated that predation by golden eagles accounted for 90% of fox mortalities observed during the Santa Cruz Island study (Roemer 1999). A collaborative effort among island managers is now underway to remove golden eagles from the northern islands (S. Morrison, TNC, pers. comm.).

Human activities likely 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 livestock or carrion). For example, on Santa Cruz Island, golden eagles had opportunities to feed on pigs and other introduced herbivores (Roemer 1999). On Santa Rosa Island, the presence of introduced mule deer and elk likely supports breeding golden eagles, in the form of fawns in the spring, and carcasses during the fall hunting season (Coonan 2003). A simulation model suggested that the fox population alone could probably not have supported the number of eagles observed on Santa Cruz Island over an extended time period, suggesting 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 can damage fox habitat, particularly streamside vegetation in canyon bottoms, and may impact water sources (Van Vuren 1984). Pigs were introduced to the Channel Islands in the 1850s (Junak et al. 1995) and found on Santa Rosa Island until 1992 (Lombardo and Faulkner 2000).

Second, the extirpation of bald eagles due to organochlorine contamination by the late 1950s (Kiff 1980) may have removed an effective competitor of or deterrent to golden eagles. Lastly, grazing by domestic livestock may have changed vegetation composition and structure, thereby reducing available cover and making foxes more susceptible to eagle predation (Roemer 1999, Roemer et al. 2001b).

Because of its vast grassy hills and lack of predators, Santa Rosa Island has long been popular with ranchers. Domestic sheep, elk, mule deer, pigs, cattle, and horses were all introduced to the island (Laughrin 1973). Large numbers of domestic sheep were grazed on the island until the early 1900s, cattle were removed from the island in 1998, and feral horses were found on the island until at least 1999 (Schoenherr et al. 1999). Today, mule deer and elk, introduced in the early 1900s, are the only nonnative herbivores remaining on the island, with plans for their removal in 2011 as part of a 1998 agreement with the owners of the elk and deer herds (T. Coonan, NPS, pers. comm.).

The damage of extensive overgrazing is apparent on many parts of the island, with sparse vegetation and extensive erosion visible in many areas. Livestock removal has reduced the impact, but vegetation recovery may take years. In the meantime, invasion by exotic plants presents a management challenge, and the lack of vegetative cover may make island foxes more susceptible to predation by golden eagles (Coonan 2003, Coonan et al. 2004).

Although no large-scale disease die-off has been reported for foxes on Santa Rosa 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 may increase their susceptibility to novel diseases (Wayne et al. 1991). For this reason, introduction of novel diseases, particularly those introduced by dogs and other animals brought to the island by humans, presents a constant and serious risk.

The Channel Islands have a depauperate terrestrial mammalian fauna, resulting in few natural competitors and few prey species (Laughrin 1971). Today, island foxes on several islands may experience competition from feral cats. On Santa Cruz and Santa Rosa islands, island foxes are sympatric with island spotted skunks, an endemic subspecies of the western spotted skunk (Crooks 1994), and there may be competition for food resources between these species (Laughrin 1973). However, spotted skunks were relatively rare on Santa Cruz Island in 1970 (Laughrin 1971), and trapping and observational data from 1991-1993 on that island suggested that the two species differed in spatial, dietary, and temporal use of resources (Crooks 1994, Crooks and Van Vuren 1995). However, Roemer (1999) reported an increase in skunk captures on both Santa Cruz and Santa Rosa Islands during a decline in the fox population, suggesting that competition does occur between the two species. On Santa Cruz Island, capture success for skunks was 1.3% while the fox population was large, and then increased to 8.8% 5 years after the fox population had declined; this higher trap success could, however, have been due to more empty traps being available when fewer foxes were present.

Near the end of 2003, 12 foxes were released from captivity to re-establish a wild population on Santa Rosa Island (Coonan et al. 2004). Additional animals have been released in recent years, and the current wild population is approximately 40 animals, with an additional 42 animals in captivity (T. Coonan, NPS, pers. comm.). While there is still some eagle predation on the island, no breeding golden eagles were documented in 2006, for the first time since about 1996-1997, providing hope that eagle predation may decrease (Coonan and Dennis 2006).

7.2 Monitoring Objectives

<u>Parameters for tracking recovery</u>

- Annual estimate of island-wide population size, with an 80% confidence interval. The point estimate should ideally 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.
- Habitat- and site-specific density.
- Reproduction measured in terms of annual recruitment.
- 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.

7.3 Past and Current Monitoring

7.3.1 Summary of Past and Current Trapping Protocols

The first known quantitative study of Santa Rosa Island foxes was conducted in 1972 to examine: (a) distribution and relative abundance, (b) food habits and availability, and (c) threats (Laughrin 1973). In that study, two lines of 15 traps, set at intervals of 320 meters (0.2 mile), were established in two different vegetation associations─one primarily in grassland and one in a mixed vegetation area. Each line was trapped for 4 days during March 1972. All areas visited were searched for signs of fox use, and scat was collected to assess food habits.

Data collected from that field effort included sex ratios, age structure, reproductive status (number of lactating females), general health and body condition, and distances moved between captures. An index of trap success was recorded, and a density estimate was generated for each line of traps, assuming that each transect sampled an area 800 meters (0.5 mile) wide. This assumption was based on the average distance moved by recaptured individuals on San Clemente Island (Laughrin 1973). An island-wide population estimate was initially generated by multiplying these density estimates by the entire island size, but the researcher stated that he abandoned this approach due to the "inappropriateness" of applying these possibly unreliable estimates to the entire island (Laughrin 1973). A minimum count of individual foxes trapped in the two areas was recorded, and a Lincoln-Petersen estimate was generated for each of the two areas; however, Laughrin (1973) stated that differences in the trapline design and violations of assumptions inherent to the Lincoln-Petersen estimate reduced the usefulness of this estimate. Different fox densities were observed between the two habitat types, leading the researcher to suggested that future monitoring methods should (a) trap various islands as close in time as possible, (b) sample all major habitat types, and (c) use repeat sampling (Laughrin 1973). Laughrin (1973) also noted that a trapping design using a grid pattern would likely produce a more reliable density estimate than one using transects.

No formal field studies were conducted on Santa Rosa Island between the 1970s and the late 1990s. In 1998, Roemer (1999) trapped foxes along transects on Santa Rosa Island and the other five islands inhabited by island foxes, as part of a cross-island comparison of density. Traps were set approximately 200 meters apart, for 6 nights, for a total of 132 trap-nights. Trap results were presented as trap success, which was used to compare abundance trends across islands.

In 2000, further transect trapping totaling 989 trap-nights was conducted in response to observed declines on the neighboring islands of San Miguel and Santa Cruz, with the primary purpose of finding as many individuals as possible. However, the population had already dropped to very small numbers, and capture success and observations of fox sign on the island were low (Coonan 2003). By 2000, the population had been reduced to 14 animals, and these individuals were brought in to a captive breeding program on the island (Coonan et al. 2004).

Beginning in late 2003, 12 foxes were released from captivity to re-establish a wild population on the island (Coonan et al. 2004). Additional animals have been released in recent years, and the current wild population is approximately 40 animals. Released animals as well as trapped wild-born animals are all radiocollared and monitored to track survival and causes of mortality. Signals are monitored daily for the first month, three times per week during the second month, and at least once per week for the remainder of the year (Coonan and Dennis 2006). Survival and causes of mortality are being compared among age groups, and between released and wild-born animals, to better understand the current survival rates in the wild including the influence of captivity. In addition, seasonal patterns of eagle predation are being documented.

Survival of collared animals is estimated with the Kaplan-Meier procedure with staggered entry (Pollock et al. 1989, Coonan and Dennis 2006). All mortalities are investigated and fox carcasses are submitted for necropsy at UC Davis. Automated cameras have been set up near den sites to monitor the numbers of pups in wild litters. Focused trapping in the home range of targeted animals' home ranges has been used to replace collars or to insert PIT tags into wild-born pups, generating data on health, body condition, relative abundance (trap success) on portions of the island, an index of reproduction, age structure, and sex ratios. In addition, dispersal patterns from release sites are recorded, as are general habitat use patterns (general location on the island; Coonan and Dennis 2006).

7.3.2 Representation Analysis of Current Trapping Protocols

There are no standardized trapping protocols currently being used on Santa Rosa Island, so we did not analyze representation.

7.3.3 The Ability of Existing Protocols to Meet Current Objectives

Early studies of Santa Rosa Island foxes produced valuable information, including relative estimates of density in two habitat types, age structure, sex ratios, and animal health. Current monitoring of the newly established population is also providing important information, especially relative to survival patterns. In this section we discuss the adequacy of existing protocols to address current monitoring objectives (Section 7.2). We recognize that previous 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

As there is currently no established trapping protocol on the islands, data for estimating population size are not being generated. Population estimates could potentially be generated with the use of camera "traps" (Karanth and Nichols 1998, Efford et al. in press), requiring a systematic camera placement with multiple cameras set along an established grid.

Survival, cause-specific mortality rates, and reproduction

Since 2003, all animals released from captivity have been radiocollared and tracked for survival. In addition, all animals subsequently born in the wild have been radiocollared at capture once they are large enough to wear a radiocollar. During the past year, approximately 25-30 radiocollared animals have been monitored for survival and cause-specific mortality. Several factors may limit the ability of this effort to generate robust estimates of survival and cause-specific mortality to meet current monitoring objectives:

1. Current survival monitoring may not be frequent enough to determine causes of death in many cases. Once the animal has been released (or collared in the case of wild-born animals) for 2 months, signals are checked only once per week (Coonan and Dennis 2006). This level of monitoring is likely adequate for monitoring eagle predation (i.e., carcasses would likely be investigated rapidly enough to determine this cause of death), but it would likely not be adequate for disease surveillance. For current monitoring protocols, pathologists suggest that animals be checked at the minimum every 2-3 days in the winter and every 1-2 days in the summer, with an ideal scenario of daily checks, to increase the chance of meaningful necropsy results.
2. Adequate numbers of collared animals may not be monitored throughout the year. At least 40 animals should be radiocollared and monitored at all times of the year. Therefore, additional animals should be radiocollared and monitored. In addition, if collar batteries do not last for an entire year, there may be a period when all collars from the previous year's annual trapping have expired batteries. Unless trapping is conducted between annual trapping surveys, or pulse rates on collars are slowed so that battery life is ≥12 months, there may be periods when inadequate numbers of animals are monitored.

Trends in population abundance or density

Santa Rosa Island currently has no established trapping protocol, except for variable targeted trapping for collaring animals; therefore, trap data for estimating population trends are not being generated. Camera trapping currently conducted on the island provides some information, such as number of weaned pups per litter, but unless cameras are set up in a systematic fashion with standardized effort and locations between years and among habitat types, they will not provide adequate information on trends.

7.4 Monitoring Protocols for Santa Rosa Island

7.4.1 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 Santa Rosa Island must consider the following specific issues:

1. The island is very rugged, which makes fieldwork difficult (Maps 7-3 and 7-4). Approximately 36% of the island has terrain with slopes greater than 30% (16.7°) which, according to NPS management, is the maximum terrain steepness feasible for fieldwork.
2. Although there is a fairly extensive system of roads and trails, the island's large size constrains monitoring activities, such as daily signal checks from the ground, because of the time involved in traveling across the island. In addition, approximately 11% of the island is more than 1 km from existing roads accessible by four-wheel-drive vehicles, and off-road vehicle use is prohibited. Effective field work in these areas requires increased field personnel to carry traps and other equipment on foot and to access all set traps within a reasonable time frame.
3. Access to some parts of the island is limited seasonally due to elk and mule deer hunting. The primarly hunt season occurs during mid-August to mid-December, and a secondary hunt season occurs during most of May. Approximately 90% of the island is hunted, and access to hunted areas is limited. Biologists may enter the hunt area at certain times for short time periods, but extended activites such as consecutive days of trapping are not feasible during these periods. This restriction is expected to be eliminated after 2011, when deer and elk are to be removed from the island.
4. The coastline from (and including) Skunk Point south to East Point is closed to entry from March 1-September 15 to protect nesting snowy plovers (*Charadrius alexandrinus*).

7.4.2 Candidate Trapping Protocols

As described in Section 2.4.1, we had two options for trapping protocols on Santa Rosa Island: transect-based trapping using multiple small units and island-wide random trapping (Box 2-2).

We first evaluated the feasibility of island-wide random trapping. Although we did not analyze the use of this method on Santa Rosa Island specifically, analyses were conducted to examine the feasibility of this method on San Miguel, San Nicolas (Appendices K and L), and Santa Cruz (data not shown). Due to the large number of traps and nights of trapping that would be required by this method on Santa Cruz Island (80-120 traps, moved each night for at least 15 nights, data not shown), this method would not be feasible on any of the three larger islands (Santa Catalina, Santa Rosa, Santa Cruz); we therefore abandoned this option for Santa Rosa Island.

We explored the use of transects, which could be more practical in rugged and steep terrain than larger grids (Appendix M). 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. Therefore, 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 (Appendix M). Given a particular trap layout and duration, 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 M). Simulations were run at a range of densities, and detection parameters were set at a range of plausible values as well as a best estimate of detection scenarios, generated by V. Bakker using actual trap data from multiple years and multiple islands, and the program DENSITY.

Simulation results suggested that 33 recaptures would be necessary to obtain a mean $CV(\hat{D}) = 20\%$, and that 40 recaptures would further assure that this precision was obtained in most runs (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 in the same appendix shows the number of units required to obtain 40 recaptures at varying densities. The latter (40 recaptures) therefore provides a more conservative goal, which would assure a $CV(\hat{D}) \leq 20\%$. Our goal was to identify logistically feasible scenarios that would obtain at least 33 recaptures and, based on number of expected recaptures, we estimated expected precision with the equation $CV(\hat{D}) = 0.894m^{-0.297} - 0.116$, where m = the number of recaptures (Appendix M).

At the current fox density on Santa Rosa Island (estimated to be 0.2 fox/km^2), simulation results suggest that the use of as many as 30-35 units (2,160-2,520 trap-nights) would result in a $CV(\hat{D})$ of only 40%, and that many more units would be required to obtain the target precision at current densities (Appendix M). We concluded that it is infeasible to obtain the target precision at current estimates within a reasonable field effort, and that a better option would be to establish a protocol that will provide adequate precision once population density increases to 1 fox/km^2. Until that time, the protocol would provide an estimate with lower precision, which would likely be used in conjunction with the MNKA, based primarily on collared animals. Although the MNKA does not provide a valid population estimate, it may serve to shorten the confidence intervals on $\hat{N}$ estimates by truncating the lower interval.

Based on simulations, a protocol with 24 units would likely provide a density estimate with precision $CV(\hat{D})$ of 45-48% at the current population size, with precision increasing to $CV(\hat{D})$ of 20-22% if/when density increases to 1 fox/km^2 (Appendix M). We propose this scenario as Santa Rosa Island Trapping Scenario A. We developed a map of this scenario by placing (and orienting) the 24 units randomly on the island, using the following rules: (a) units must originate on or near a road, (b) units must be ≥1,500 meters apart to reduce the chance of an individual fox moving between grids, (c) trap locations should avoid steep slopes with ≥30% (16.7°) slope to reduce risks to field personnel (Map 7-5). Although it is possible to place units closer to each other, 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.

In the event that this extent of trapping is infeasible, the number of units could be decreased, but at the expense of reduced precision. For example, a scenario with 18 units would likely result in a precision, CV($\hat{D}$), of 55-60% at current densities, which would likely improve to 20-22% if/when density increases to 1.7 foxes/km^2 (Appendix M). We propose this as Santa Rosa Island Trapping Scenario B, and provide a map of this scenario, created with the same steps as for Scenario A (Map 7-6).

There is no correct answer on scenario choice, and variations of the scenarios are possible, for example, by randomly eliminating units from either scenario. The final choice will depend on the trade-off between effort expended and desired precision, which will depend in part on population density and recapture rates. At any density, Scenario A, with 1,728 total trap-nights, will provide better precision and representation of habitat variation than Scenario B, but will be more labor-intensive. We provide Scenario B, with a total of 1,296 trap-nights, as an option that may be more feasible with a limited field crew. The expected precision of either scenario 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.).

One of the monitoring objectives for Santa Rosa Island is to estimate density by major habitat types to help guide management. This may be especially feasible with Scenario A, because this scenario will sample habitat variability on the island most completely. The influence of various habitat covariates could potentially be examined using multivariate analyses, and unit-level habitat covariates can be incorporated into analyses in the program DENSITY. Research on habitat selection and home-range size, using locational data from radiocollared animals, would also shed light on differences in habitat quality across the island landscape (Section 7.5.3).

7.4.3 Representation Analysis of Selected Candidate Trapping Protocols

To determine how well selected candidate trapping protocols represent habitat variability on Santa Rosa Island, we conducted representation analyses using both univariate and multivariate techniques, and compared the two candidate protocols (Scenarios A and B) to habitat variability of the entire island (Appendices D and I).

Univariate analyses (Appendix D) indicate that areas sampled by Scenarios A and B differ statistically from island-wide areas in all continuous habitat measures, with the exception of distance to developed areas, which does not differ between the island and Scenario A, and distance to roads, which doesn't differ between the island and Scenario B. It is possible, however, that these statistical differences may not indicate biological differences because, in most cases, absolute differences are quite small in relation to the scale of measurement (e.g., slope and ruggedness) or in comparison to fox movement distances (e.g., distance to the shore, distance to freshwater; Appendix D). For example, distance to freshwater is significantly different, but medians and means of island-wide versus trapped areas differed by <50 meters, which may not have relevance to fox habitat selection. Because a map of freshwater sources was lacking for this island, we used a 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. It is unknown if a difference of 50 meters has relevance to selection or avoidance of ravines and drainages. Although Scenario B tends to resemble the island most closely in terms of slope, distance to roads and freshwater, and possibly ruggedness, Scenario A samples the island better in terms of distance to the shore and developed areas, and in vegetation composition.

Multivariate analyses (Appendix I) also indicate that steep terrain on Santa Rosa Island is under-sampled by both proposed trapping scenarios. This bias towards level terrain occurs regardless of proximity to development and roads. Steep terrain far from drainages, however, appears better sampled (i.e., PC3), suggesting that avoidance of canyons may have contributed to this pattern. Unlike many other islands, steep shoreline areas are not under-represented by either proposed trapping scenario on Santa Rosa Island. Both proposed scenarios appear to perform similarly in terms of multivariate representation, although Scenario B samples steep, rugged, remote terrain somewhat better. Thus, the additional trapping grids in Scenario A do not increase the multivariate representativeness of this sampling design. 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.

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. In addition, density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to ensure that these biases do not bias monitoring program results.

7.4.4 Survival and Cause-Specific Mortality Monitoring

Due to the large size and relatively rugged terrain of Santa Rosa Island, frequent ground monitoring of radio signals will be difficult without a large investment of personnel hours and vehicles. Even if a full-time person and vehicle were dedicated to the task of monitoring 40 foxes distributed across the island, this task may not be feasible, due to large rugged areas not accessible by road or trail. Currently, 20-30 foxes are tracked remotely from the ground, and aerial tracking is used occasionally to locate foxes not detected from the ground.

The use of remote telemetry receivers could be considered as an alternative or an addition to ground monitoring on this island (see Section 2.4.2). However, assuming a detection range (the distance over which a collar signal can be detected assuming a line-of-sight signal) of 5 km, a large number of tall towers would likely be necessary to detect foxes on Santa Rosa Island. A preliminary viewshed analysis suggested that nine 45-meter high towers with a 5-km detection range would not adequately monitor San Clemente Island, which is smaller and has less rugged terrain than Santa Rosa Island. A viewshed analysis would be needed to determine the necessary number and most effective placement of towers, based on their height, and to determine portions of the island that would be monitored effectively by the remote system. Prior to the viewshed analysis, the detection range of collars should be confirmed in the field.

We suggest that a promising monitoring approach for Santa Rosa Island may be aerial monitoring from an airplane. As described in Section 2.4.2, aerial monitoring may be an effective strategy on the three largest islands (Santa Catalina, Santa Rosa, and Santa Cruz) and an option that should be explored is the idea of the three islands (SCIC, NPS, and TNC) jointly contracting a pilot and airplane to monitor the three islands on a regular basis. This may reduce the collective cost of monitoring foxes on the three islands and would provide a time-efficient and thorough method for monitoring foxes on this island.

Other options that should be explored, as discussed in Section 2.4.2, are the use of GPS collars or a combination of ground monitoring and remote telemetry monitoring. For the latter, personnel hours would need to be dedicated for regular monitoring of areas accessible by existing roads and trails, and remote monitoring towers could be placed strategically to detect signals in areas difficult to access from the ground. For example, a viewshed analysis could be conducted to identify all areas that could be monitored from existing roads and trails on a regular basis. Placement of remote towers could then be evaluated to detect signals from the remaining parts of the islands. If field personnel are unable to check the entire island frequently enough, monitoring efforts can be split geographically so that half of the island is checked one day and the other half is checked the next day.

We suggest that survival estimation be performed with the known fate model in MARK, rather than the simple Kaplan-Meier estimator.

7.5 A Tiered Approach for Population Monitoring

7.5.1 Recommended Long-Term Trapping Protocols

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

- Scenario A: 24 units of 2x6 traps, for a total of 1,728 trap-nights annually (Map 7-5)
- Scenario B: 18 units of 2x6 traps, for a total of 1,296 trap-nights annually (Map 7-6)

Trapping should be conducted at the same time each year and be synchronized with timing on other islands to facilitate accurate comparisons across years and islands. We suggest that July represents the 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.

7.5.2 Recommended Monitoring for Survival and Cause-Specific Mortality

To address a primary monitoring objective outlined in Section 2.4.2, and to track survival and cause-specific mortality for Santa Rosa Island foxes, we recommend the following actions:

1. Annually radio-collar at least 40 foxes with mortality-sensing collars (Section 2.4.2). These foxes should be widely distributed across the island. 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 or composition of 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. Explore the option of aerial signal monitoring, ideally in collaboration with monitoring efforts on Santa Catalina and Santa Cruz islands. If feasible, contract pilot and airplane to conduct routine (ideally daily, but at least every other day during summer) monitoring of all radiocollared foxes.
3. If aerial monitoring is not feasible, explore the option of a remote monitoring system to augment ground monitoring.
    - 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 identify areas that can be monitored via telemetry from established roads and trails.
    - Conduct a viewshed analysis to determine number and locations of towers necessary to monitor animals in areas where ground-monitoring is not feasible. 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).
    - Dedicate personnel hours needed to assure that signals are checked in all the ground-monitoring areas at a minimum of 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.
    - If the above investigations warrant the use of remote telemetry on towers, construct towers and install and test the automatic recording system.
4. Explore the use of GPS collars to monitor survival, as discussed in Section 2.4.2.
5. Have personnel on call on the island to immediately locate and investigate mortalities, and develop a protocol for transporting carcasses to UC Davis for necropsy.

7.5.3 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 Santa Rosa Island include:

1. Habitat and space use**.** Habitat and space use studies should examine specific behavioral and demographic patterns relative to roads, human activity, specific vegetation types (including successional stages of vegetation recovering from grazing), water sources, and shoreline areas. These data will be useful, for example, 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). In addition, studies on home range size, movement patterns, habitat selection, and dispersal, especially as these relate to density, will increase our understanding of habitat quality differences which could lead to source-sink dynamics. In addition, further information is needed on fox-skunk relationship, including population dynamics and habitat-use relationships. The presence of radiocollared animals (for survival monitoring) will greatly facilitate such studies.

2. Factors influencing survival. Long-term survival monitoring data (Section 7.5.2) should help identify factors that influence survival rates using covariates within known fate models in program MARK or Cox proportional hazards modeling (Cox 1972). For example, such an analysis could be used in combination with locational data on radiocollared animals to test whether increased use of open habitat such as grassland increases the risk of eagle predation. This could have relevance to decisions on managing exotic herbivores and restoring habitat where livestock have been removed.

3. Disease and health**.** Although standardized disease and health monitoring will be conducted every year, 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.

4. Reproduction and early pup survival. Although annual trap data may provide some information on reproduction (e.g., indexed by the proportion of captured females exhibiting signs of reproduction, or by the observed ratio of yearlings to females), further research is needed on reproduction, early 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 (via scat or hair sampling) may be necessary.

5. Vegetation. Based on the ecological response to removal of sheep from Santa Cruz Island, and the recent removal of cattle from Santa Rosa Island (Wagner et al. 2004), it is expected that the vegetation coverage of Santa Rosa Island will change dramatically in the coming decades and that those changes will have appreciable effect on fox population dynamics. Therefore, an island-wide vegetation map should be completed and updated every 5-10 years. As part of this effort, field work should measure vegetation height, structure, and composition at fixed sites to track changes due to habitat recovery, climate change, and human activity. These data will be useful for understanding temporal and spatial patterns of fox habitat use.

6. Effectiveness of remote telemetry stations. If aerial monitoring of fox survival is not feasible for the long-term, the use of remote monitoring systems should be explored to

augment survival monitoring efforts on the ground. This should include determining actual, in-field, detection ranges for telemetry signals as a function of terrain, location, tower heights, etc., and the number and locations of towers needed to monitor the island adequately (Section 7.5.2).

7. Impacts of nonnative herbivores. A study should examine the impact of nonnative herbivores (elk and mule deer) on fox habitat quality and indirectly on fox survival. Data collected as part of habitat use and survival studies (#1 and 2 above) could be incorporated into the planned removal of these herbivores by 2011 to evaluate changes in fox habitat use, selection, and survival after the herbivores are removed and as habitat recovers.

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.

   On Santa Rosa Island, the presence of skunks creates an additional challenge related to trapping protocols, because capture of skunks reduces the number of traps available to foxes. Further research and analysis on how to best account for this issue, and how the prior capture of a skunk influences subsequent capture of a fox in the same trap, will help refine future trap protocols.

Section 3.2 outlines additional non-fox data that should be routinely monitored and integrated with fox data.

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Santa Rosa Island

Map 7-1 Basemap

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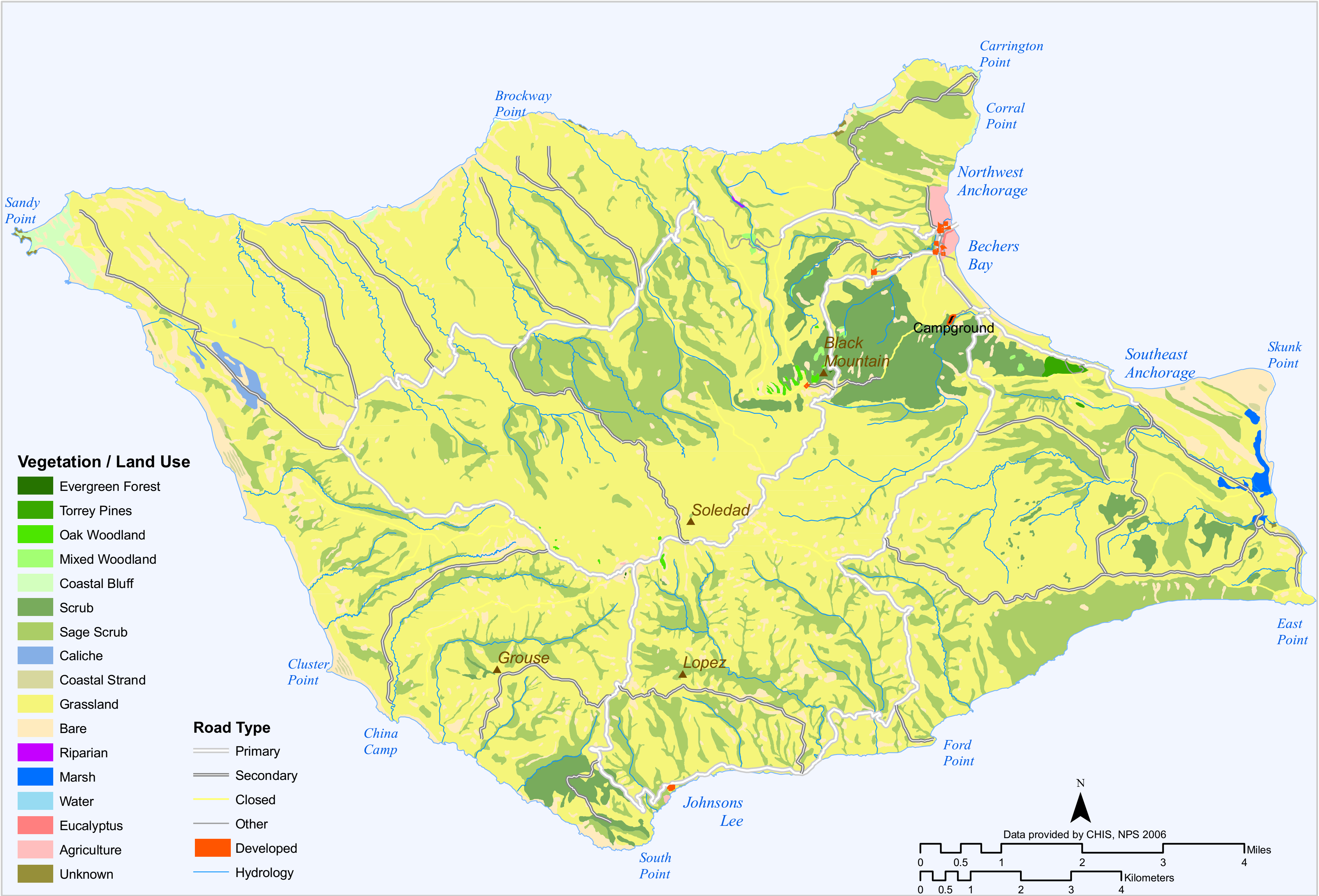
Santa Rosa Island

Map 7-2 Vegetation



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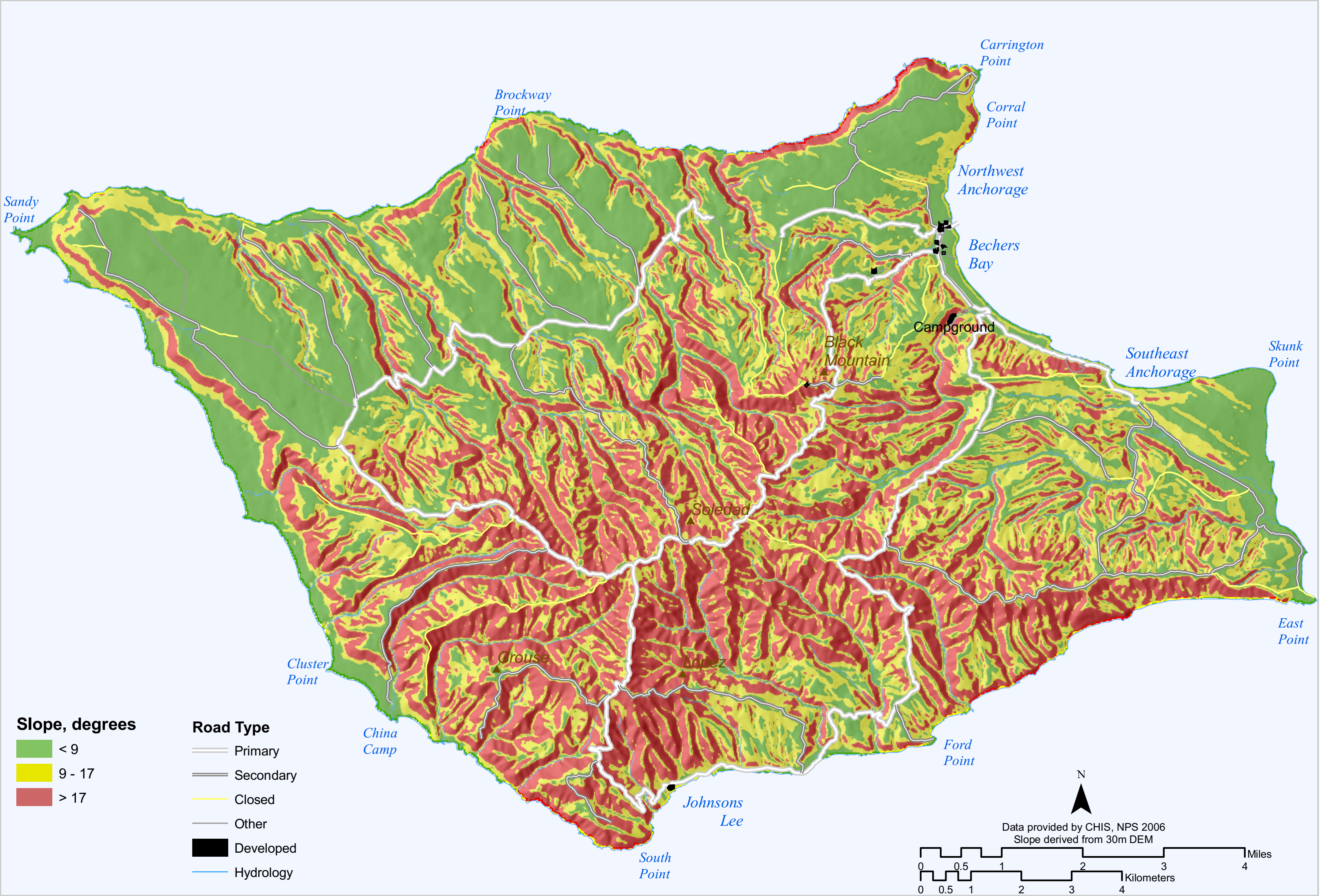
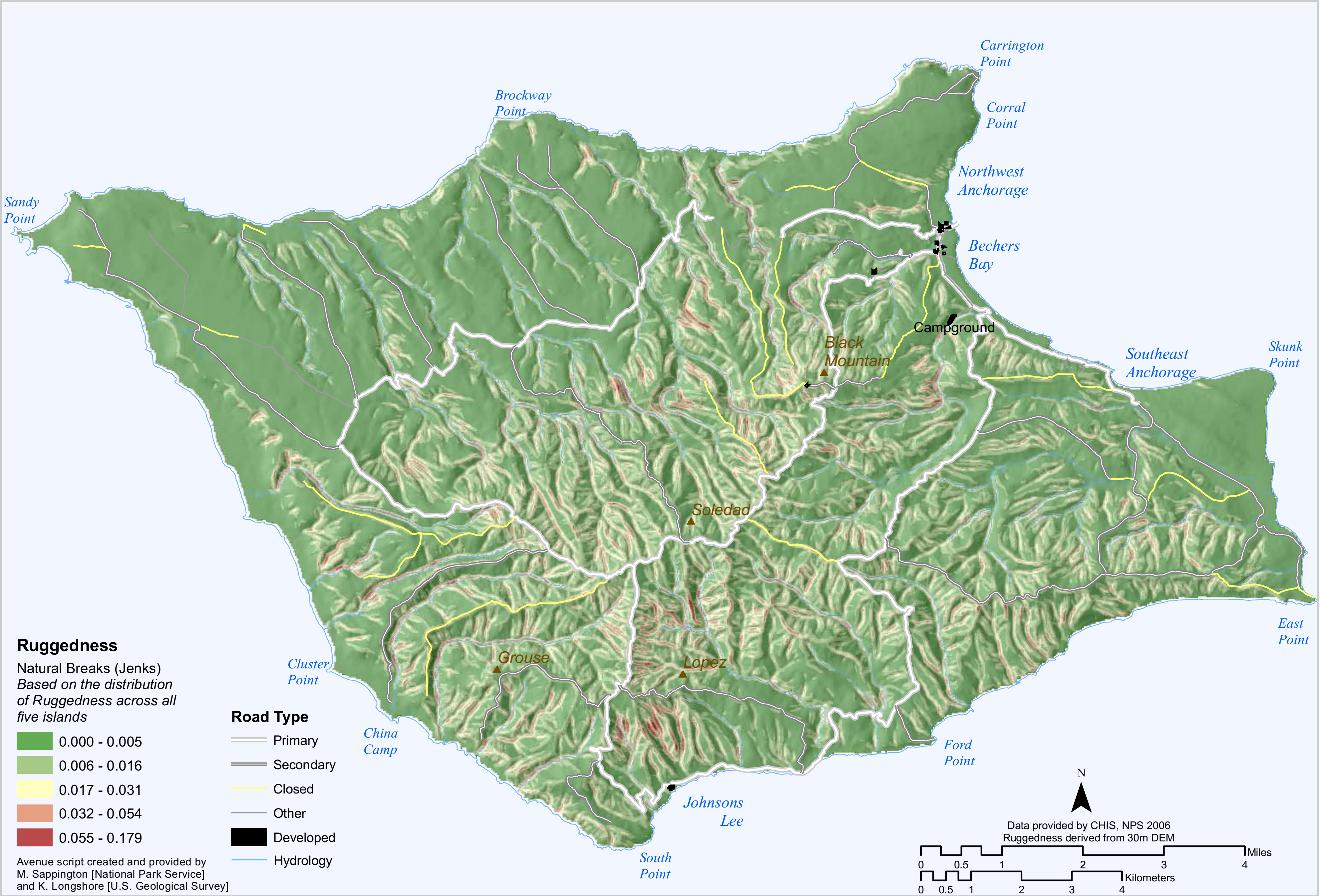
Map 7-3 Slope



Santa Rosa Island

Map 7-4 Ruggedness



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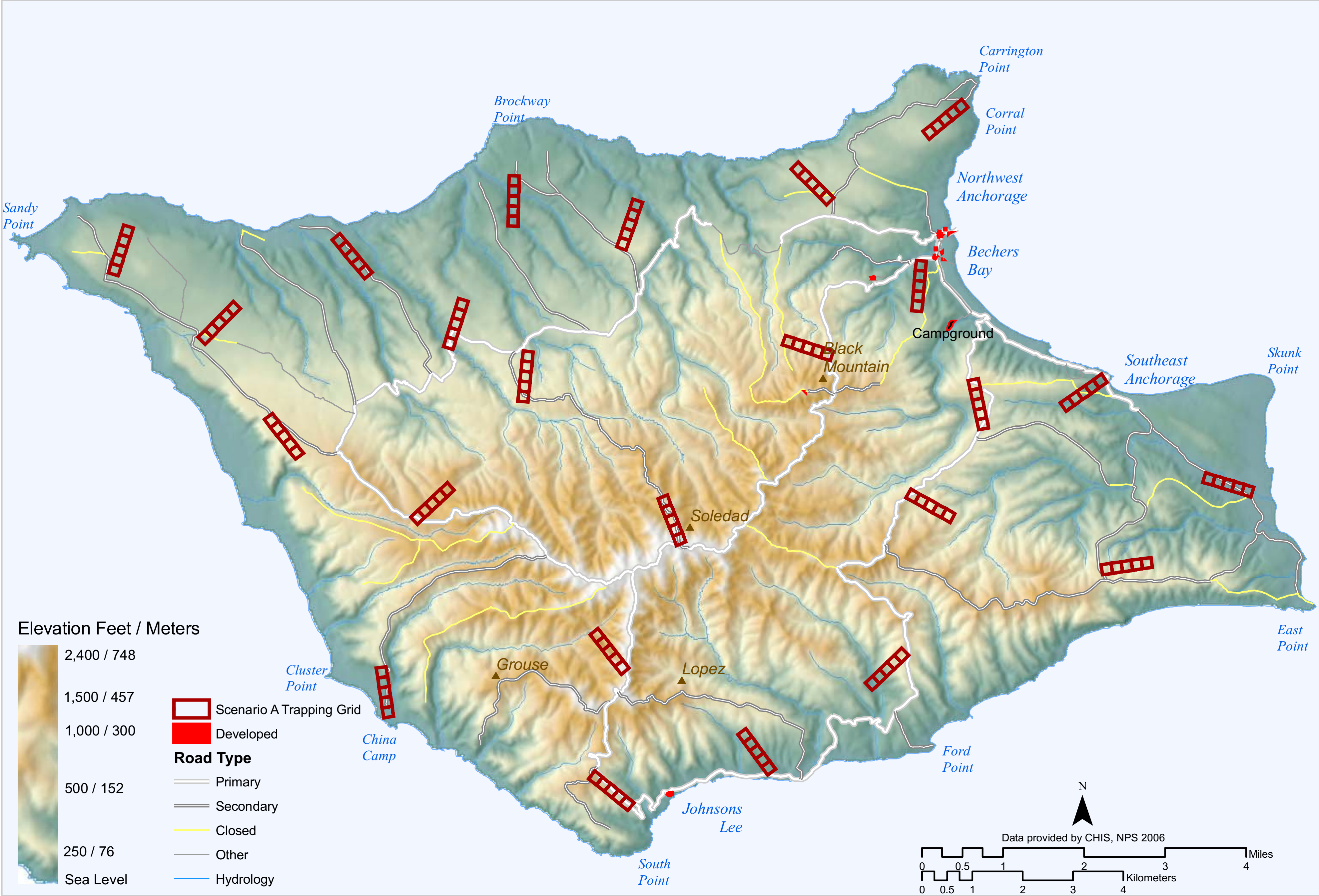
Map 7-5 Trapping Scenario A



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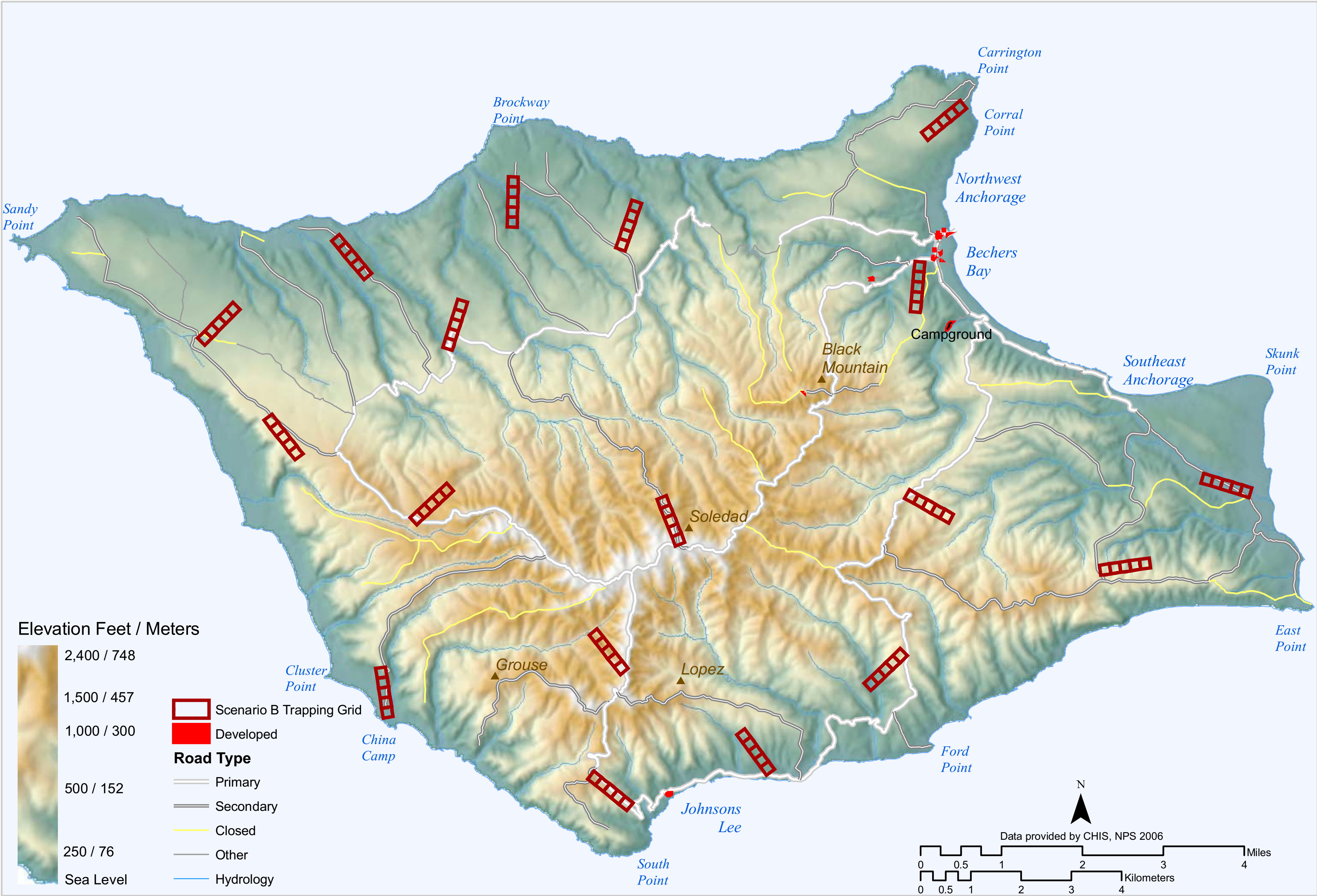
Map 7-6 Trapping Scenario B



8 A Monitoring Plan for Santa Cruz Island Foxes

With an area of 249 km^2, Santa Cruz Island is the largest of the eight Channel Islands, with an approximate length of 38 km (24 miles) and a width of 3-11 km (1.9-6.9 miles; Table 1-1; Laughrin 1973). Its eastern edge is 30 km (19 miles) from mainland California (Schoenherr et al. 1999; Map 1-1). Historically, the island was owned by two landowners: the Santa Cruz Island Company and another private landowner (Laughrin 1973). In 1978, 90% of the island was effectively purchased by and came under the protection of The Nature Conservancy; the remaining portion came under the ownership and protection of the National Park Service in 1997 (Schoenherr et al. 1999). Today, TNC owns 76% of the island and NPS owns 24%.

A dominant feature of Santa Cruz Island's topography is the east-west running Central Valley, situated along a geological fault and flanked by two mountain ranges (Van Vuren and Coblentz 1987; Map 8-1). To the north of the valley lies a rugged ridge with elevations of 750 meters (2,461 feet), where slopes exceed 30°, and to the south lies a smaller mountain range with elevations of 465 meters (1,526 feet; Laughrin 1973, Van Vuren and Coblentz 1987). Most of the coastline is composed of precipitous cliffs. The Central Valley has a semi-continental climate and may experience freezing temperatures during the winter (Laughrin 1971).

The diversity of terrain and temperature, along with the availability of year-round fresh water in many canyons, support a higher diversity of habitat types and species than any other Channel Island (Schoenherr et al. 1999; Map 8-2). Santa Cruz Island supports at least 45 nesting bird species, 480 native plant species, and 12 native mammalian species, including the island spotted skunk (*Spilogale gracilis amphialus*, Laughrin 1973, Schoenherr et al. 1999). Major vegetation types include grassland (36% of the island), chaparral and coastal sage scrub (48% of the island), and woodland and forest communities (10% of the island; Minnich 1980, cited in Van Vuren and Coblentz 1987). Laughrin (1973) reported that foxes on Santa Cruz Island used all these habitat types (Map 7-2).

8.1 Santa Cruz Island Foxes

Foxes on Santa Cruz Island were first described by C. H. Merriam in 1903 (Laughrin 1971). As on other Channel Islands, fox populations have experienced periods of low density in past years (Laughrin 1971). Numbers were higher prior to 1918, when ranch hands killed foxes to reduce damage to ranch vineyards (Laughrin 1980). During a museum collecting trip in 1948, no foxes were observed during 23 days of field work, and only four individuals were trapped (Bills 1969, cited in Laughrin 1973).

Higher numbers were again observed during field work in 1970, leading Laughrin (1971) to describe the population size as "...unlikely to be greater than 3,000." Based on further trapping in 1973, Laughrin (1973) concluded that densities on Santa Cruz Island were high compared to other islands, which he attributed to the high habitat diversity and food abundance. He also noted that animals captured in 1973 were mostly young, healthy animals. Further trapping conducted during 1973-1977 resulted in density estimates higher than those documented on other islands, and field data suggested a stable population during this time period (Laughrin 1980).

During 1991-1993, Crooks (1994) trapped foxes as part of a comparative ecology study of foxes and island skunks. Although trap success was lower than reported by Laughrin (1980), foxes were observed to be "…abundant and easily captured." The difference in trap success observed in Crooks' (1994) study versus that observed by Laughrin (1980) could have been due to difference in trapping design or due to traps being set in different habitat or at different times of year. Crooks (1994) interpreted a high proportion of young animals to indicate an increasing population.

Based on field work conducted in 1993, Roemer et al. (1994) estimated the population on Santa Cruz Island to be 1,465 foxes. However, by 1998 the population was estimated at only 232 animals (Roemer 1999), and by 1999 at only 133 foxes (Roemer et al. 2001b). Predation by golden eagles was suspected of causing this decline (Roemer 1999). Roemer (1999) reported that between 1995 and 1998 the populations on Santa Cruz and San Miguel dropped by 90% and the estimated time to extinction was 5-17 years. Population modeling and sensitivity analyses showed that survival of pup and adult foxes, and fertility of adult foxes, had the greatest influence on population growth rate compared to other demographic parameters, and field data showed that these parameters had changed the most during the years of decline (Roemer et al. 2002a). On Santa Cruz Island, survival across all age classes decreased during the study period, and adult fertility decreased during 1993-1998. Roemer (1999) suggested that a captive breeding program could increase pup survival, and he recommended removal of golden eagles and reintroduction of bald eagles as restoration actions.

It is believed that golden eagles first colonized the northern Channel Islands in the early 1990s, with the first reported sightings in 1993 (Roemer 1999, Roemer et al. 2001b). Golden eagle sightings and fox predation increased on the northern islands during 1993-1998, with low fox survival rates leading to near extirpation of the wild population (Roemer 1999, Roemer et al. 2001b). During this period, fox captures and density estimates on two capture grids decreased, and it was estimated that predation by golden eagles accounted for 90% of fox mortalities observed during the study, with golden eagles linked to 19 of 21 known fox mortalities on the western end of Santa Cruz Island (Roemer 1999). Eagle predation and associated fox population declines were also documented on San Miguel and Santa Rosa islands (Roemer 1999). Fox populations on the southern Channel Islands (San Nicolas, San Clemente, and Santa Catalina) remained relatively stable during this same time period, although the San Clemente fox population decreased at a slower rate over a 10-year period (Roemer et al 2001b). An ongoing collaborative effort among island managers is underway to remove all resident golden eagles from the islands (S. Morrison, TNC, pers. comm.).

Human activities likely promoted the presence of golden eagles on Santa Cruz Island. 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). A simulation model suggested that the fox population alone could probably not have supported the number of eagles observed on Santa Cruz Island over an extended time, leading the authors to conclude that feral pigs were subsidizing the predator's diet, thus contributing to the decline of fox populations on the northern islands (Roemer et al. 2001b). Feral pigs also cause severe damage to fox habitat, particularly streamside vegetation in canyon bottoms, and may impact water sources (Van Vuren 1984). An effort by TNC and NPS to remove pigs on the northern islands is nearing completion (Morrison et al. 2007). The extirpation of bald eagles due to organochlorine contamination by the late 1950s (Kiff 1980) may have removed an effective competitor of or deterrent to golden eagles. Finally, grazing by domestic livestock may have changed vegetation composition and structure, thereby reducing available cover and making foxes more susceptible to eagle predation (Roemer 1999, Roemer et al. 2001b).

Although Santa Cruz Island has had limited human development compared to other Channel Islands, it has nonetheless been heavily impacted by livestock grazing (Laughrin 1973). Domestic sheep were grazed on the island starting in the 1850s (Brumbaugh 1980, cited in Van Vuren and Coblentz 1987), and the island at times supported over 50,000 sheep (Van Vuren and Coblentz 1987). Over time the sheep became increasingly feral until routine annual round-ups became impossible, and shooting and trapping were implemented as control measures in the early 1900s (Van Vuren and Coblentz 1987). During 1979-1980, 20,000 feral sheep were estimated to occupy the island, along with other introduced mammals including feral pigs and domestic cattle (Van Vuren and Coblentz 1987). State wildlife agencies recommended that all exotic mammals on the island, most being grazers, browsers, or up-rooters of native vegetation, should be removed (CDFG 1987). Most sheep were removed in the 1980s, with the remaining 2,000 sheep removed in the late 1990s, but the damage from long-term overgrazing is still evident (Crooks and Van Vuren 1995, Schoenherr et al. 1999). Van Vuren and Coblentz (1987) noted that about half of the island had been moderately to severely impacted as a result of defoliation and trampling. By the early 1990s, cattle grazing was also eliminated (Beatty and Licari 1992, cited in Crooks 1994). The cessation of grazing pressure is thought to have facilitated an invasion of an exotic plant, fennel (*Foeniculum vulgare*), to spread through many of the grassland communities on the island (Crooks 1994).

Although no large-scale disease die-off has been reported for foxes on Santa Cruz 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 may increase their susceptibility to novel diseases (Wayne et al. 1991). For this reason, introduction of novel diseases, particularly those introduced 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 exposure to five potentially lethal diseases and checked for heartworm and parasites, and these samples were compared to disease profiles from 1988 (Roemer et al. 2000, Roemer et al. 2001b). Roemer et al. (2001b) found no concordance between pathogen prevalence and the temporal and geographic pattern of population decline. No canine distemper virus was found in any of the five subpopulations sampled, and parvovirus 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 1997-98), 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.

The Channel Islands have a depauperate terrestrial mammalian fauna, resulting in few natural competitors and few prey species (Laughrin 1971). On Santa Cruz and Santa Rosa islands, island foxes are sympatric with island spotted skunks, an endemic subspecies of the western spotted skunk (Crooks 1994). Spotted skunks were, however, reported to be relatively rare on Santa Cruz Island in 1970 (Laughrin 1971). Trapping and observational data from 1991-1993 also suggest that spotted skunks were relatively rare compared to island foxes, and that the two species differed in spatial, dietary, and temporal use of resources (Crooks 1994, Crooks and Van Vuren 1995). However, Roemer (1999) reported that an increase in skunk captures was observed on both Santa Cruz and Santa Rosa islands during the decline of the fox population, suggesting that competition does occur between the two species. On Santa Cruz Island, trap success for skunks was 1.3% while the fox population was large, and it increased to 8.8% 5 years after the fox population had declined. However, this higher trap success could have been due to more empty traps being available when fewer foxes were present.

The Santa Cruz Island fox population has been brought back from near extinction, primarily through the establishment of an active program to remove golden eagles and pigs from the island, and a captive breeding program that provides a safety net for the population. There are currently an estimated 264 foxes in the wild (Schmidt et al. 2007), and 33 in captivity (R. Wolstenholme, TNC, pers. comm.).

8.2 Monitoring Objectives

<u>Parameters for tracking recovery</u>

- Annual estimate of island-wide population size, with an 80% confidence interval. The point estimate should ideally 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.

<u>Parameters for island-specific management decisions</u>

- Cause-specific mortality rates by age and sex, considering all causes of mortality.
- Habitat- and site-specific density.
- Habitat- and site-specific survival.
- Disease and health profiles, as sampled from all dead foxes and from a subset of the living population based on sampling protocols determined by the Fox Health TEG.

8.3 Past and Current Monitoring

8.3.1 Summary of Past and Current Monitoring Protocols

The first known quantitative study of Santa Cruz Island foxes was conducted in 1970 (Laughrin 1971). In that study, 609 trap-nights resulted in 230 captures of 198 individual foxes (Laughrin 1971). This provided preliminary data on sex ratios, age structure, general distribution, weights, and body condition.

In 1973, additional field work was conducted to examine: (a) distribution and relative abundance, (b) food habits and availability, and (c) factors affecting the welfare of the population (Laughrin 1973). Traps were set up in three different lines; the first line of 30 traps set in a 3x5 grid pattern with two traps at each station, and the two lines set out as linear transects, with traps placed 160-320 meters (0.1-0.2 mile) apart (Laughrin 1973). Trapping occurred during March 1973, and each line was trapped for 3-4 days. The three trap lines each traversed multiple habitat types. In addition, all areas visited were searched for signs of fox use, and scat was collected for diet analysis. Data collected from this field effort included sex ratios, age structure, reproductive status (based on number of lactating females), general health and body condition, and distances moved between captures. An index of trap success was recorded, and a density estimate was generated for each line of traps, assuming that each transect sampled an area 800 meters (0.5 mile) wide. This assumption was based on the average distance moved by recaptured individuals on San Clemente Island (Laughrin 1973). An island-wide population estimate was initially generated by multiplying these density estimates by the entire island size, but Laughrin (1973) abandoned this approach due to the "inappropriateness" of applying these possibly unreliable estimates to the entire island. Different fox densities were observed among different habitat types, causing Laughrin (1973) to suggest that future monitoring methods should sample all major habitat types. He further suggested that various parts of the islands be trapped as close in time as possible, that repeat sampling be used, and that a grid trapping design would likely produce a more reliable density estimate than one using transects (Laughrin 1973).

Laughrin (1980) conducted further trapping on Santa Cruz Island during seven trapping sessions in 1973-1977 to assess abundance in different habitats and during different years. Thirty traps were placed in lines along roads or trails, with a spacing of 320 meters (0.2 mile), and trapped for 3 days (Laughrin 1980). Trap lines were placed in the same areas within two habitat types (chaparral and woodland) each year, because sightings and sign indicated that these were high density areas. Data obtained from this field effort included age structure, sex ratio, body condition, and general health. In addition, as in previous years, trap success was recorded, and an estimate of density was generated for each transect (Laughrin 1980).

In 1991-1993, Crooks (1994) conducted a comparative ecology study on the island fox and the sympatric island skunk to examine relative abundance, sex ratios, age structure, and variation in weight by age, sex, and season for both species. The study was conducted at two locations on the island─Rancho del Norte, at the northeastern side of the island, primarily dominated by fennel-invaded grasslands, and Central Valley, dominated by chaparral and grasslands (Crooks 1994). Although the purpose of trapping was to radiocollar animals, demographic data were collected during the trapping effort. Traps were set along movement routes and other activity areas. This effort provided data on sex ratios, age structure, weight, and body condition. Population density estimates were not generated, but trap success rates (overall and by season) were used as an index of relative abundance. In addition, six foxes in each study area (three males and three females) were radiotracked during 11 months in 1992 to collect data on home range, daily activity, and habitat preference (Crooks and Van Vuren 1995, 1996). Locations were estimated 3-5 times per week via triangulation, and home ranges were generated using the adaptive kernel method (Worton 1989). Habitat selection was examined, based on availability of various habitat types in each of the two study areas, and scat samples were collected for diet analysis.

During 1993-1998, Roemer et al. (1994) trapped to assess population size and demographic parameters. Two grids were established, with locations chosen to represent dominant habitat types and to avoid areas heavily impacted by humans and areas of steep and rugged topography. The two grids covered 2.1% of the island (Roemer 1999). The first grid, referred to as the Central Valley or Mixed grid, consisted of 5x10 traps in grassland, chaparral, oak woodland, coastal sage scrub, and riparian habitat. The second grid, referred to as the Fraser Point or Grass grid, was 5x13 traps in grassland and coastal dune scrub habitat. Trap spacing was 250 meters, traps were set for 5-7 consecutive days, and trapping was conducted from late May to early September. The two grids were trapped for 5 years (1993 and 1995-1998; Roemer 1999).

Population size estimates were generated for each of the grids using the program CAPTURE (White et al. 1982) and Chapman's modification of the Lincoln-Petersen method (Seber 1982). The latter method was included as a comparison method because model selection in the program CAPTURE may not be robust with small sample sizes (Roemer et al. 1994). 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, Roemer et al. 1994).

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." Developed, barren, and cultivated areas were omitted from the calculations (Roemer et al. 1994).

Of foxes captured during 1993-1995, a subset of individuals near Fraser Point at the west end of the island was included in a study designed to (a) examine the spatial distribution, relatedness, and mating system of island foxes, and (b) document the impact of eagle predation on survival, population density, and fox behavior (Roemer 1999). Twenty-five foxes belonging to 11 social groups or *families* were tracked intensely (with locations every 2-3 days) for a period of approximately 1 year (November 1993-December 1994), and then less intensely (about twice per month) until the end of the study in September 1995. A larger sample of animals was included in a genetic analysis of relatedness and mating systems. Monthly survival of radiocollared foxes was calculated using the Kaplan-Meier staggered entry design (Pollock et al. 1989, Roemer 1999), and apparent survival was also estimated separately from 1995-1998 grid trapping data using the Cormack-Jolly-Seber model in program MARK (White and Burnham 1999). The study provided information on home ranges, space use overlap among paired and unpaired animals, dispersal and estimates of gene flow, estimates of genetic relatedness, mating system, reproduction (number of pups trapped), survival and cause-specific mortality rates, activity patterns, and disease exposure (Roemer 1999).

In 1998, Roemer (1999) trapped foxes along transects on Santa Cruz Island and the other five islands inhabited by island foxes as part of a cross-island comparison of density (Roemer 1999). Traps were set approximately 200 meters apart, for 6 nights, for a total of 76 trap-nights. Trap results were presented as trap success to compare abundance across islands.

In 2001, the Institute for Wildlife Studies began monitoring population size, distribution, and productivity to examine the effects of golden eagle predation on the population. That year, trapping was distributed as widely as possible across the island, to assess population status following the reported decline caused by golden eagles (Roemer 1999, Schmidt et al. 2007). Starting in 2002, foxes were trapped along transects distributed across the island, primarily along roads, trails, and ridges, excluding steep and rugged terrain, with traps set approximately 300 meters apart. Twelve transects of 35-49 traps were each trapped for 4 consecutive nights during June through November (Schmidt et al. 2007, R. Wolstenholme, TNC, pers. comm.).

That field effort, which has been continued annually since 2002, generates data on sex ratios, age structure, health and body condition, and preliminary data on survival. In addition, trap data are used to generate an estimate of island-wide abundance by using MNKA and extrapolating this number to unsampled portions of the island. The area sampled is determined by assuming an effective trap radius of 500 meters around each trap (minus overlap). Approximately 41% of Santa Cruz Island is sampled by this trapping effort (Schmidt et al. 2007).

In 2006, a 1-km^2 grid was overlaid on the island and, based on the number of individual foxes captured in each grid cell, a mean and standard deviation of fox density was generated (foxes per km^2). This number was used to extrapolate to the unsampled areas. Population size was estimated by adding MNKA to the number estimated as being in the unsampled areas (Schmidt et al. 2007).

A subset of captured foxes and animals released from captivity were radiocollared and monitored for survival, using ground telemetry and a remote tracking station at Diablo Peak (the highest point on the island). The remote station, which uses a cell phone for remote communication to researchers, was designed to pick up signals from foxes on the north side of North Ridge. In 2005 and 2006, a total of 88 and 90 foxes, respectively, were radiocollared and monitored on Santa Cruz Island for survival, with each animal's signal checked at least once per week. Signals on a subset of about 40 animals are checked twice per week (L. Vermeer, TNC, pers. comm.). All animals found dead are sent to US Davis for necropsy.

8.3.2 Representation Analysis of Current Trapping Protocols

To determine how well existing trapping protocols represent habitat variability on the island, we conducted univariate and multivariate representation analyses (Appendices E and J). The univariate analysis suggests that the current trapping protocol does not adequately represent habitat variability on Santa Cruz Island. Trapped areas tend to be less steep, farther from the shoreline and freshwater, and closer to roads and developed areas than the average on the island (Appendix E; Maps 8-3 and 8-4). Some of these differences may not be biologically relevant, as some differences were small relative to fox movements (e.g., distance to freshwater) or are not believed to be relevant given the small absolute difference (e.g., slope; Appendix E). However, the bias toward roads and developed areas, and away from steeper areas near the shoreline, may have relevance if density or survival of foxes differs with these habitat factors.

We also performed a principal components analysis (PCA) for key habitat attributes, comparing mean principal component (PC) scores for trapped areas to those of the entire island. Transect trapping on Santa Cruz Island has greatly under-represented remote shoreline and interior canyons. Once accounting for topography linked to proximity to shoreline and freshwater (i.e., canyons), steep and rugged habitat was sampled in proportion to its availability. Existing transects appear to sample vegetation proportionally to its occurrence on the island. Nonetheless, under-sampling of remote shoreline and interior canyons occurs systematically in all vegetation types.

8.3.3 The Ability of Existing Protocols to Meet Current Objectives

Previous and ongoing studies of Santa Cruz Island foxes have produced a wealth of valuable information, including data on population trends, estimates of density, age structure and sex ratios, animal health, and survival. In this section we discuss the adequacy of existing protocols to address current monitoring objectives (Section 8.2). We recognize that previous 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

Although field data have been used to generate an island-wide population estimate for Santa Cruz Island, several shortcomings limit the accuracy and precision of these estimates:

1. Current trapping is along transects which can provide relative abundance indices. However, transect sampling is typically not used to generate density estimates using traditional mark-recapture analysis methods and, in general, data from transect sampling do not provide estimates of abundance or density as precisely as grid trapping data. A

primary shortcoming of transect trapping is the difficulty of estimating effective trap area around the transect (Spencer et al. 2006, Schmidt and Garcelon 2003). However, we recognize the challenge of trapping grids on steep and rugged terrain, and suggest that transect sampling may be necessary. Fortunately, newly developed methods of spatially explicit capture-recapture analysis (Efford 2004) should allow use of modified transect configuration on large rugged islands (Section 8.4.2).

2. Grids were trapped on the island for 5 years (1993, 1995, 1996, 1997, and 1998; Roemer et al. 1994, Roemer 1999) and resulting data provided robust grid-specific density estimates and abundance estimates. However, the two grids represented a small portion of the island and didn't adequately represent habitat diversity on the island, so data can not be confidently extrapolated to the entire island.

3. Current trapping protocols are biased towards areas near roads and development, and away from steep areas such as the shoreline.

4. The current method of determining the portion of the island sampled (adding a 500-meter radius around each trap) assumes that distances moved in various habitat types, and at various population densities, remain constant, when this is actually not known. In fact, distances moved (and resulting home ranges) can vary by season, habitat, island, sex, density, and age (Moore and Collins 1995). In addition, the method of overlaying a 1-km^2 grid on the entire island and generating a mean and standard deviation of fox density from capture data to be applied to un-sampled portions of the island may be problematic. It is not clear if this approach corrects data for capture effort per grid cell. That is, a cell including several traps might be weighted the same as a cell with only one trap. Furthermore, this method does not appear to consider different densities in different habitats. This approach also does not include a way of estimating sampling error. Finally, this approach appears to assume that all foxes in the cell are captured, rather than accounting for capture probability using mark-recapture methods.

5. The current trapping protocol is labor-intensive and costly, approaching an island census rather than an estimate based on sampling methods.

Survival and cause-specific mortality rates

Although annual capture data on marked animals can be used to estimate apparent survival rates, they do not reveal mortality causes or distinguish between mortality and emigration, and they do not facilitate immediate management response in the event of a disease outbreak or sudden increase in predation. After the population decline in the mid-1990s and subsequent reestablishment of the population, a large number of animals have been radiocollared and monitored for survival. For example, during 2005 and 2006, at least 70 radiocollared foxes were monitored for survival at any one time[6], providing preliminary data on survival and cause-

[6] Some models had suggested that the removal of feral pigs from Santa Cruz Island could have the effect of increasing the mortality rate of foxes due to golden eagle predation (Courchamp et al. 2003). The increase in the number of collared foxes during that period was intended to provide enhanced monitoring through that period of hypothesized heightened risk for the foxes.

specific mortality rates. However, several factors may limit the ability to generate robust estimates of survival and cause-specific mortality:

1. Current survival monitoring may not be frequent enough to determine causes of death. Signals on about 40 animals are checked twice weekly, and the remainder are checked once per week (R. Wolstenholme, TNC, pers. comm.). This frequency is likely adequate for monitoring for mortalities due to eagle predation (because carcasses could be investigated soon enough to determine cause of death), but it would not be adequate for disease surveillance during summer months. The Fox Health TEG suggests that animals be checked at least every 2-3 days in the winter and every 1-2 days in the summer, with an ideal scenario of daily checks, to increase the chance of meaningful necropsy results.
2. It is not known if adequate numbers of collared animals are monitored throughout the year. If collar batteries do not last for an entire year, there may be a period when the number of functional collars decreases. Unless additional trapping is conducted between annual trapping surveys, or if pulse rates on collars are reduced to extend battery life to ≥12 months, there may be periods when inadequate numbers of animals are monitored.
3. Currently, radiocollared foxes may not be representative of the entire population. Few animals are captured and monitored on the north side of North Ridge, due to steep and rugged terrain, and poor access. Based on the distribution of known golden eagle nest sites, however, the north side may support more golden eagles than the remainder of the island (S. Morrison, TNC, pers. comm.); thus, foxes in this area may be at higher risk of golden eagle predation. A remote telemetry monitoring station on Mount Diablo was designed to aid in monitoring signals from foxes on the north side of North Ridge (along north beaches and in north facing canyons); however, this monitoring system has worked with limited success (R. Wolstenholme, TNC, pers. comm.). It is possible that future survival monitoring will also under-represent the north side of the island and, in this situation, managers should be aware that island-wide survival could be under-estimated if foxes on the north side do indeed have lower survival; something that could be especially problematic if the north slope functions as a "sink" for the island population overall. We suggest that this be investigated in a focused research project (Section 8.5.3).
4. It is not clear how well the wild population is represented by the monitored sample. Ideally, sampled animals should include males and females, with an age distribution representative of the population. Although pups should be included in this sample, we recognize the current challenges of monitoring pup survival, because their small size precludes use of radiocollars. We suggest that further research be conducted to develop methods of estimating pup survival (Section 8.5.3).

Trends in population abundance or density

The extensive transect trapping that occurs every year on Santa Cruz Island may provide a useful index of changes in density. It is even possible that a less intensive effort could provide such an index, with trap success used to establish indices of relative abundance over time. However, several aspects of the trapping protocols could be improved and standardized to make year-to-year data more comparable and more amenable to standard analysis methods:

1. Trap success alone should not generally be used as an index but instead should be corrected for capture probability.
2. Some inter-annual variation apparently exists in trap locations, and this could cause inter-annual variability in trapping results. Standardized transects should be trapped at the same locations every year, with the same inter-trap distances, because inter-trap spacing can influence capture probabilities. Ideally, reports should show actual trap locations or provide coordinates to help standardize trap locations.
3. The number of traps and areas trapped has changed across years, making trap data less useful for assessing trends. For example, on the northwestern end of Santa Cruz Island, transects were abandoned after several years of low trap success, most likely due to personnel or budget limitations, when it would have been ideal to continue these transects to monitor long-term trends or shifts in distribution. However, the purpose of that protocol may not have been to monitor population trends, and obtaining other data (e.g., minimum number known alive) may have been a priority. Given that abundance trends are now a desired monitoring product, a trapping protocol, once established, should remain consistent across years, so that trends can best be recognized.
4. Some inter-annual variation exists in the timing of trapping, which may also influence trap results. To provide the best data for assessing population trends, standardized transects should be trapped at the same time every year. Transects should be trapped according to a standardized schedule during the annual trapping period, and the trapping period should be standardized among islands.
5. 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.
6. Sampling is not distributed across the island to represent all habitat types and geographic areas. We recognize that this will likely be impossible with any feasible trapping protocol, due to Santa Cruz Island's rugged and steep terrain. We therefore suggest that (a) an attempt is made to distribute trapping across the island as much as possible, and (b) 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 8.5.3).

Existing data have provided an estimate of past abundance trends. However, the above improvements could increase accuracy and precision of trend estimates.

Survival and density by habitat type

Current monitoring protocols are unlikely to provide robust density estimates by habitat type. Improved placement of transects in combination with newly developed analytical techniques, such as those implemented in the program DENSITY (Efford 2004), may help stratify density estimates by habitat, as recommended for island fox monitoring on San Clemente Island (Spencer et al. 2006). If strict random placement is chosen and multiple sampling units are used, multivariate analyses could be used to examine the influence of various habitat attributes (Section 8.4.2) Research on habitat selection and home-range size, using locational data from radiocollared animals would also shed light on differences in habitat quality across the island landscape (Section 8.5.3).

Current protocols do not provide a way to monitor survival by habitat type. However, radio-location data would allow analysis of time spent in each habitat type.

8.4 Monitoring Protocols for Santa Cruz Island

8.4.1 Feasibility Considerations for Monitoring Activities

Section 2.2.2 outlined 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 Santa Cruz Island must consider the following specific issues:

1. The island is very rugged, which makes fieldwork difficult (Maps 8-3 and 8-4). Approximately 61% of the island has terrain with slopes greater than 30% (16.7°) which, according to NPS management, is the maximum terrain steepness feasible for field work.
2. Although there is a fairly extensive system of roads and trails, the island's large size constrains some monitoring activities, such as daily signal checks from the ground. Approximately 36% of the island is more than 1 km from existing roads accessible by four-wheel-drive vehicles, and off-road vehicle use is prohibited. Effective field work in these areas requires increased field personnel to carry traps and other equipment on foot and to access all set traps within a reasonable time frame.
3. Lack of roads limits access to areas north of North Ridge and limits travel between the east end of the island, owned by NPS, and the remainder of the island. Housing and transportation for field crews is also limited on the easternmost 10% of the island, which must be accessed by boat.

8.4.2 Candidate Trapping Protocols

As described in Section 2.4.1, we had two options for trapping protocols on Santa Cruz Island: transect-based trapping using multiple small units, and island-wide random trapping.

We first evaluated the feasibility of island-wide random trapping. Using 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 desired precision. In this simulation, traps were placed in random locations across the island each night and then moved to new random locations on each subsequent night. Results indicate that adequate precision ($CV[\hat{N}] \leq 20\%$) could be obtained only if 80-120 traps were trapped and moved each night for at least 15 nights, or if 200 traps were trapped and moved for 5 nights (data not shown). Due to the logistical challenge of moving ≥80 traps to a new location for every trap occasion (night) on this large and rugged island, this method was deemed impractical by Santa Cruz Island biologists, and we therefore abandoned this option for Santa Cruz Island.

We also explored the use of transects, which could be more practical in rugged and steep terrain than larger grids would be (Appendix M). Simulation results indicate that parallel paired lines (referred to here as units) produce better results than single straight lines with the same number of traps and spacing (Appendix M). Simulations were also used to evaluate the number of traps, trap-spacing, and number of nights trapped that would provide the best precision in relation to effort (Appendix M). Based on these results, we chose to use a standard trapping unit with dimensions of 2x6 traps, spaced at 200 meters and trapped for 6 nights, in further evaluations of trap effort versus resulting precision, with the primary question being how many such units would be required to obtain adequate precision (Appendix M). Given a particular trap layout and duration, resulting precision depends largely on the number of recaptures. Recaptures, in turn, are determined by the fox density and behavior, 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 M). Simulations were run at a range of densities, and detection parameters were set at a range of plausible values as well as a best estimate of detection scenarios, generated by V. Bakker 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.

Simulation results suggest that 33 recaptures (collectively across all units on the island during the complete annual capture session) are necessary to obtain a mean CV($\hat{D}$) = 20%, and that 40 recaptures would further assure that this precision is obtained in most runs (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 in the same appendix 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($\hat{D}$) ≤20%. Our goal was to identify logistically feasible scenarios that would obtain at least 33 recaptures and, based on number of expected recaptures, we estimated expected precision with the equation CV($\hat{D}$) = $0.894m^{-0.297}-0.116$, where m = the number of recaptures (Appendix M).

At current fox densities on Santa Cruz Island (estimated to be 1.02 fox/km^2), simulation results suggest that a protocol with 24 trapping units would provide a density estimate with the targeted precision, with CV($\hat{D}$) simulated to be 20-21% (Appendix M). We propose this scenario as Santa Cruz Island Trapping Scenario A. We developed a map of this scenario by placing (and orienting) 24 units randomly on the island, using the following rules: (a) units must originate on or near a road, (b) units must be ≥1,500 meters apart to reduce the chance of an individual fox moving between grids, (c) trap locations should avoid steep slopes with ≥30% (16.7°) slope to reduce risks to field personnel (Map 8-5). Although it is possible to place units closer to each other, maintaining at least 1,500 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.

If this level of effort is infeasible, a smaller number of units could be trapped, but at the expense of precision. For example, if 18 units were trapped, resulting CV($\hat{D}$) would be 22-23% at the current population size, and would improve to the targeted precision if density increased to 1.7 foxes/km^2. We propose this scenario as Santa Cruz Island Trapping Scenario B, and produced a map with units located in the same manner as for Scenario A (Map 8-6).

There is no *correct* answer on scenario choice, and variations of the two scenarios defined above are possible. The final choice will depend on the trade-off between effort expended and desired precision, which will depend in part on population density and recapture rates. At current densities, Scenario A, with 1,728 total trap-nights, will provide good precision and the best habitat representation. If this level of effort is deemed impractical, units could be eliminated randomly to make the protocol more feasible. We provide Scenario B, with a total of 1,296 trap-nights, as a more feasible but less precise and representative approach.

The expected precision of either of these two scenarios could likely be increased by increasing the number of nights trapped (because this would increase the expected number of overall recaptures); 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.).

8.4.3 Representation Analyses of Selected Candidate Trapping Protocols

To determine how well selected candidate trapping protocols represent habitat variability on Santa Cruz Island, we conducted representation analyses using both univariate and multivariate techniques and compared habitat representation resulting from the two candidate protocols (Scenarios A and B) to habitat variability of island-wide areas as well as those sampled by the existing protocol (Appendices E and J).

Univariate analyses (Appendix E) indicate that areas sampled by all three trapping scenarios have lower slope than island-wide areas, and Scenario B additionally samples areas with lower ruggedness. This is not surprising, as logistic and safety constraints require that traps are not placed in steep and rugged terrain. These differences may not have an influence on trap results, however, because absolute differences were small (Appendix E). The existing trapping protocol and Scenario A both sample areas that differ from island-wide areas in distance to shore, but the absolute differences are small relative to fox movement patterns and may, therefore, not have biological relevance. Although all three trapping scenarios sampled areas closer to roads (as was expected, as traps were placed in proximity to roads for logistic reasons) and to developed areas, compared to island-wide areas, this difference was most extreme in the existing protocol. It is possible that this may bias trap results, if foxes select or avoid areas close to roads and developed areas. Although all three trap scenarios did not sample vegetation categories in proportion to their availability on the island, Scenario A sampled these most adequately.

Multivariate analyses (Appendix J) indicate that existing transects and proposed Scenario A under-represent roadless, remote shoreline characteristic of areas on the north, west, and the south sides of the island, while Scenario B represents this feature consistent with its overall presence on the island. Existing transects and both proposed scenarios under-sample remote steep and rugged interior areas to a similar degree. Proposed scenarios over-sample rugged terrain on flatter ground. Overall, Scenario B appears to represent the habitat characteristics of the island best, despite fewer trapping units overall. This efficiency is achieved because most of the additional trapping units comprising Scenario A occur in areas closer to roads and development, which tend to be over-sampled. 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.

We suggest that habitat use and selection be examined in radiocollared foxes to determine which, if any, of the above habitat differences might bias trap results. In addition, density and demographic rates in disproportionately-sampled habitat types should be compared to overall island-wide patterns to ensure that these biases do not bias monitoring results.

8.4.4 Survival and Cause-Specific Mortality Monitoring

Due to the large size and rugged terrain of Santa Cruz Island, frequent ground monitoring of radio signals will be difficult without a large investment of personnel hours and vehicles. Even if a full-time person and vehicle were dedicated to the task of monitoring 40 foxes distributed across the island, this task may not be feasible, especially as a large portion of the island (e.g., north of North Ridge) is not accessible by road. Currently, signals on approximately 40 foxes are checked from the ground about twice per week, and signals on the remaining 33 collared foxes are checked once per week.

The use of remote telemetry receivers could be considered as an alternative or an addition to ground monitoring (see Section 2.4.2). However, assuming a detection range of 5 km, many tall towers would likely be necessary to detect foxes across Santa Cruz Island. Remote telemetry technology has been used on the island in the form of a tower on Diablo Peak (the highest point on the island). This tower, which transfers signal information via cell phone, is currently limited in its effectiveness because it cannot detect foxes in several north-facing canyons north of North Ridge and several steep drainages on the south side of the island. A preliminary viewshed analysis suggested that nine 45-meter high towers with a 5 km detection range would not adequately monitor San Clemente Island, which is smaller and has less rugged terrain than Santa Cruz Island (B. Cohen, TNC, pers. comm.). A viewshed analysis could determine the necessary number and most effective placement of towers, based on their height, and portions of the island that would be monitored effectively by the remote system. Prior to the viewshed analysis, the detection range of collars should be confirmed in the field.

We suggest that a promising monitoring option for Santa Cruz Island may be aerial monitoring from an airplane. As described in Section 2.4.2, aerial monitoring may provide a cost-effective strategy on the three largest islands (Santa Catalina, Santa Rosa, and Santa Cruz) and an option that should be explored is the idea of the three islands (SCIC, NPS, and TNC) jointly contracting a pilot and airplane to monitor the three islands on a regular basis. This may reduce the collective cost of monitoring foxes on the three islands and would provide a time-efficient and thorough method for monitoring foxes on Santa Cruz Island.

If aerial monitoring is found to be infeasible, a combination of ground monitoring and remote telemetry monitoring should be considered as a second choice. Personnel hours would need to be dedicated for regular monitoring of areas accessible by existing roads and trails, and remote monitoring towers could be placed strategically to detect signals in areas difficult to access from the ground. For example, a viewshed analysis could be conducted to identify all areas that could be monitored from existing roads and trails on a regular basis. Placement of remote towers could then be evaluated to detect signals from the remaining parts of the islands. For example, towers could be placed on high points along the North Ridge to detect signals on the north side of this ridge. Alternatively, if field personnel are unable to check the entire island frequently enough, monitoring efforts could be split geographically so that the east half of the island is checked one day and the west half of the island is checked on alternating days, a strategy that is similar to what is currently used on Santa Cruz Island. An additional alternative is that the north shore of the island could be left void of radiocollared animals (i.e., no animals collared in that portion of the island), thereby relying on animals in the remainder of the island acting as sentinels. However, annual mortality rates may then not be representative of the island as a whole.

Finally, as described in Section 2.4.2, the use of GPS collars for monitoring survival of 40 animals may provide a cost-efficient option, depending on prices of collars. We suggest that island managers collaboratively evaluate and compare the cost efficiency of the above survival monitoring approaches, to find the most cost effective options for each island.

Estimates of habitat- and site-specific survival rate can be generated if survival data obtained by the above methods are combined with locational data on radiocollared animals. We suggest this joint approach as a research module in Section 8.5.3. We suggest that survival estimation be performed with the known fate model in MARK, rather than the simple Kaplan-Meier estimator.

8.5 A Tiered Approach for Population Monitoring

8.5.1 Recommended Long-Term Trapping Protocols

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

- Scenario A: 24 units of 2x6 traps, for a total of 1,728 trap-nights annually (Map 8-5)
- Scenario B: 18 units of 2x6 traps, for a total of 1,296 trap-nights annually (Map 8-6)

Trapping should 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.

8.5.2 Recommended Monitoring for Survival and Cause-Specific Monitoring

To address a primary monitoring objective outlined in Section 2.4.2, and to track survival and cause-specific mortality for Santa Cruz Island foxes, we recommend the following actions:

1. Annually radio-collar at least 40 foxes with mortality-sensing collars (Section 2.4.2). These foxes should be widely distributed across the island. 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 or composition of 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. Explore the option of aerial signal monitoring, ideally in collaboration with monitoring efforts on Santa Catalina and Santa Rosa (and possibly San Miguel) islands. If feasible, contract pilot and airplane to conduct routine (ideally daily, but at least every other day during summer) monitoring of all radiocollared foxes.
3. If aerial monitoring is not feasible, explore the option of a remote monitoring system to augment ground monitoring.
    - 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 identify areas that can be monitored via telemetry from established roads and trails.
    - Conduct a viewshed analysis to determine number and locations of towers necessary to monitor animals in areas where ground-monitoring is not feasible. 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).
    - Dedicate personnel hours needed to assure that signals are checked in all the ground-monitoring areas at a minimum of 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.
    - If the above investigations warrant the use of remote telemetry on towers, construct towers and install and test the automatic recording system.
4. Explore the use of GPS collars for survival monitoring (Section 2.4.2).
5. Have personnel on call on the island to immediately locate and investigate mortalities, and develop a protocol for transporting carcasses to UC Davis for necropsy.

8.5.3 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 Santa Cruz Island include:

1. Habitat and space use**.** Habitat selection and space use studies should examine specific behavioral and demographic patterns relative to roads, specific vegetation types, water sources, and shoreline areas. These data will be useful, for example, in interpreting annual trap data (e.g., to determine if over- or under-representation of certain habitats or portions of the island are likely to bias population estimates). Studies on home range size, movement patterns, and dispersal relative to density will increase our understanding of habitat quality differences and potential source-sink dynamics. In addition, further information is needed on fox-skunk relationships, including population dynamics and habitat-use relationships. The presence of radiocollared animals (for survival monitoring) will greatly facilitate such studies.
2. Factors influencing survival. One of the monitoring objectives for Santa Cruz Island is to monitor survival in relation to habitat use. Long-term survival monitoring data (Section 8.5.2) should help identify factors that influence survival rates using covariates within known fate models in program MARK or Cox proportional hazards modeling (Cox 1972). For example, such an analysis could be used in combination with locational data on radiocollared animals to test whether foxes using open habitats such as grasslands experience higher risk of eagle predation than foxes in areas of greater vegetation cover, as hypothesized by Roemer (1999). Results of this type of analysis could inform future sample selection for collared foxes based on vulnerability to mortality.
3. Disease and health**.** Although standardized disease and health monitoring will be conducted every year, as per recommendations of the Fox Health TEG, 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.
4. Reproduction and early pup survival. Although annual trap data may provide some information on reproduction (e.g., indexed by the proportion of captured females exhibiting signs of reproduction), further research is needed on reproduction, early 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 (via scat or hair sampling) may be necessary.
5. Vegetation. The island-wide vegetation map should be updated every 5-10 years. As part of this effort, field studies should measure vegetation height, structure, and composition at pre-determined sites to track changes due to habitat recovery, climate change, and human activity. These data will be useful for understanding temporal and spatial patterns of fox habitat use.
6. Effectiveness of remote telemetry stations. If aerial monitoring of fox survival is not feasible for the long-term, a study should explore the use of remote monitoring systems to augment survival monitoring efforts on the ground. This should include determining

actual, in field, detection ranges for telemetry signals as a function of terrain, location, tower heights, etc., and number and locations of towers needed to monitor the island adequately (see Section 8.5.2).

7. 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.

8. 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.

   On Santa Cruz Island, the presence of skunks creates an additional challenge related to trapping protocols, because capture of skunks reduces the number of traps available to foxes. Further research and analysis on how to best account for this issue, and how the prior capture of a skunk influences subsequent capture of a fox in the same trap, can help refine future trap protocols.

   Due to some inaccessible areas, trapping scenarios proposed for Santa Cruz Island fail to sample 12-15% of the island (Section 2.4.1), primarily areas north of North Ridge. To assess potential bias caused by lack of trapping in this stratum of the island, we recommend that methods such as genetic sampling, sign surveys, or camera traps be used to compare relative density in sampled and unsampled areas, ideally every 3-5 years.

Section 3.2 outlines additional non-fox data that should be routinely monitored and integrated with fox data.

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Santa Cruz Island

Map 8-1 Existing Traps

Elevation Feet / Meters

2,400 / 750
1,500 / 457
1,000 / 300
500 / 152
250 / 76
Sea Level

● Traps, 2005
Airstrips
Human Use

Road Type
Full Size Truck
Light Truck or Jeep
ATV only
No Vehicles

N

0 0.5 1 2 3 4 Miles
0 0.5 1 2 3 4 Kilometers

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Santa Cruz Island

Map 8-2 Existing Traps in Relation to Vegetation

Forest/Woodland: Coniferous
- Temperate Needleleaf Evergreen Forests

Forest/Woodland: Non-Coniferous
- Xeric Sclerophyll Evergreen Woodlands
- Temporarily Flooded Cold Season Deciduous Forests
- Temperate Broadleaf Sclerophyll Evergreen Forests

Shrublands
- Temperate Microphyllous Evergreen Shrublands
- Temperate Broadleaf Sclerophyll Evergreen Shrublands (Chaparral)
- Temporarily Flooded Cold Season Deciduous Shrublands
- Temperate Xeric Mixed Drought-Deciduous Shrublands

Grasslands
- Saturated Temperate Perennial Graminoids
- Seasonally or Temporarily Flooded Graminoids
- Tall Temperate Annual Graminoids, Non-Fennel
- Tall Temperate Perennial Graminoids
- Tidally Flooded Grasslands
- Tall Temperate Forblands
- Tall Temperate Annual Graminoids, Fennel

Other
- Developed
- Sparsely Vegetated / Barren
- Planted

- Traps, 2005
- Airstrips

Road Type
- Full Size Truck
- Light Truck or Jeep
- ATV only
- No Vehicles

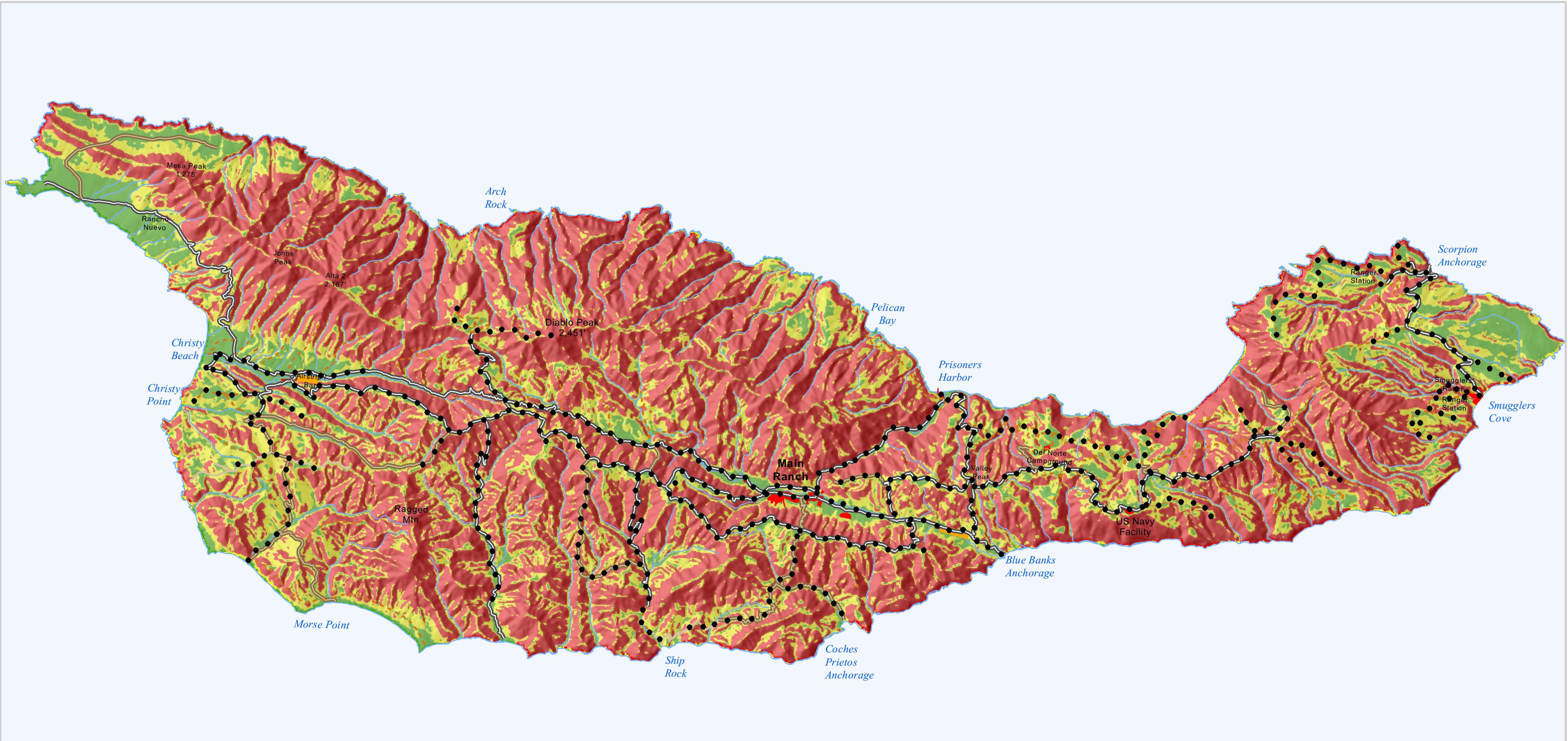
N

Vegetation data from The Nature Conservancy, 2007

Miles: 0 0.5 1 2 3 4
Kilometers: 0 0.5 1 2 3 4

Santa Cruz Island

Map 8-3 Existing Traps in Relation to Slope



Slope, degrees

- < 9
- 9 - 17
- > 17

- Traps, 2005
- Airstrips
- Human Use

Road Type

- Full Size Truck
- Light Truck or Jeep
- ATV only
- No Vehicles

N

Slope derived from 30m DEM

Miles: 0, 0.5, 1, 2, 3, 4

Kilometers: 0, 0.5, 1, 2, 3, 4

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Santa Cruz Island

Map 8-4 Existing Traps in Relation to Ruggedness

Ruggedness

Natural Breaks (Jenks)

Based on the distribution of Ruggedness across all five islands

- 0.000 - 0.005
- 0.006 - 0.016
- 0.017 - 0.031
- 0.032 - 0.054
- 0.055 - 0.179

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

- Traps, 2005
- Airstrips
- Human Use

Road Type

- Full Size Truck
- Light Truck or Jeep
- ATV only
- No Vehicles

N

Ruggedness derived from 30m DEM

0 0.5 1 2 3 4 Miles

0 0.5 1 2 3 4 Kilometers

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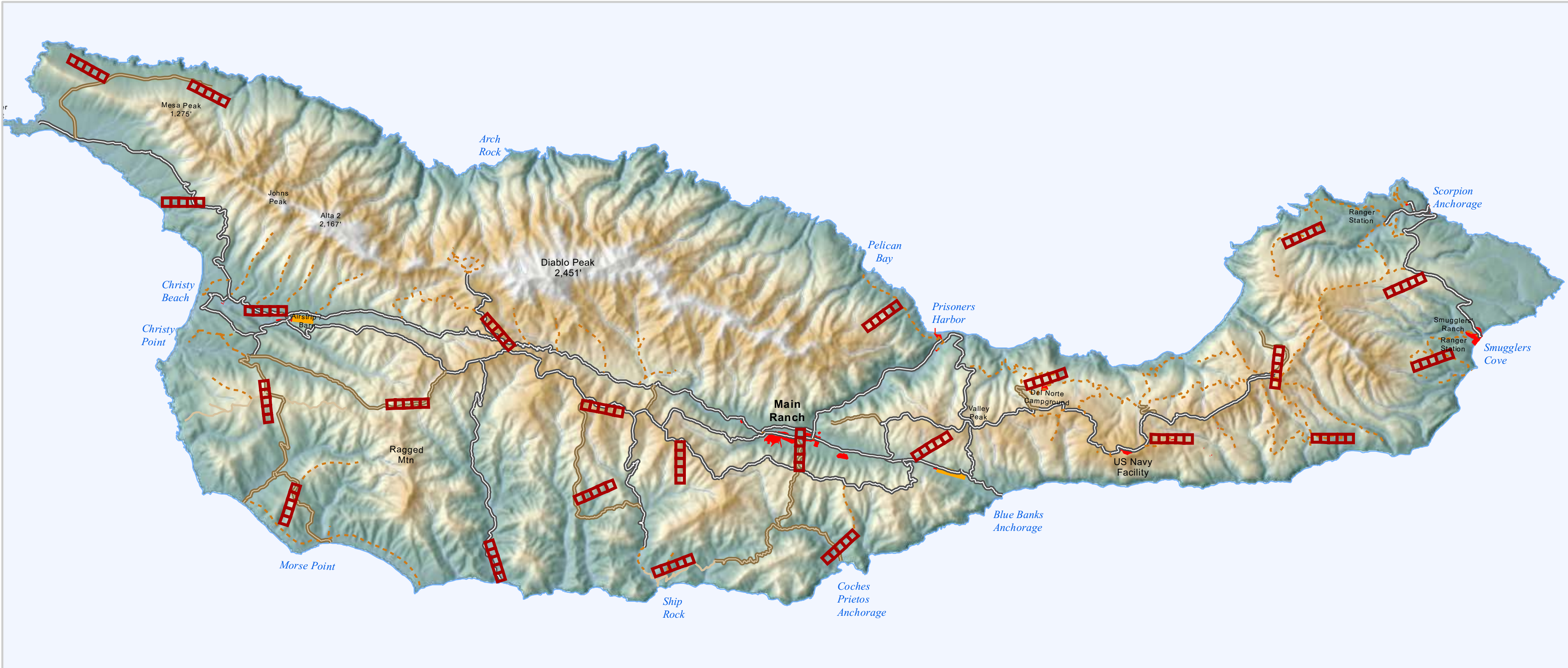
Conservation Biology Institute

Santa Cruz Island

Map 8-5 Trapping Scenario A



Elevation Feet / Meters

2,400 / 750
1,500 / 457
1,000 / 300
500 / 152
250 / 76
Sea Level

Scenario A Trapping Grid
Airstrips
Human Use

Road Type
Full Size Truck
Light Truck or Jeep
ATV only
No Vehicles

N

Miles: 0, 0.5, 1, 2, 3, 4
Kilometers: 0, 0.5, 1, 2, 3, 4

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Santa Cruz Island

Map 8-6 Trapping Scenario B

Elevation Feet / Meters

2,400 / 750

1,500 / 457

1,000 / 300

500 / 152

250 / 76

Sea Level

Scenario B Trapping Grid

Airstrips

Human Use

Road Type

Full Size Truck

Light Truck or Jeep

ATV only

No Vehicles

N

Miles: 0, 0.5, 1, 2, 3, 4

Kilometers: 0, 0.5, 1, 2, 3, 4

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APPENDICES

A. Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on San Miguel Island

B. Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on San Nicolas Island

C. Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on Santa Catalina Island

D. Univariate Representation Analysis of Proposed Trapping Scenarios on Santa Rosa Island

E. Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on Santa Cruz Island

F. Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on San Miguel Island

G. Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on San Nicolas Island

H. Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on Santa Catalina Island

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K Monitoring Island Fox Populations by Trapping and Spatially Explicit Capture-Recapture: Options for San Miguel Island

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APPENDICES A–E

Prepared by

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Appendix A

Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on San Miguel Island

Introduction

This representation analysis examines how well existing and recommended trapping protocols represent habitat variation on San Miguel Island. The goal of evaluating existing protocols was to identify gaps in island representation that could be addressed in proposed trapping scenarios, and to provide a baseline comparison with which to evaluate proposed scenarios. This information is intended to provide managers with additional information on which to base decisions about trapping protocols. In addition, increased knowledge regarding habitat representation of each trapping scenario may help identify research needs relative to habitat use and selection. In this analysis, we examined habitat representation of four trapping scenarios: (a) grids trapped during 1993-1998, (b) grids trapped in 2006 (Map 4-1), (c) trapping Scenario B (Map 4-6), and (d) trapping Scenario C (Map 4-7). Scenario A (Map 4-5) was not evaluated, as it was assumed that that scenario would provide similar habitat representation as Scenario B, possibly with slightly better representation due to larger grid size.

Methods

We identified habitat variables currently available as GIS coverages or that could be created from existing GIS coverages, and for which we have empirical evidence or biological rationale to suspect that they may influence island fox habitat quality or population dynamics. Although we can not know or measure all habitat characteristics important to island foxes, we strived to maximize representation of the following habitat attributes that we can measure: vegetation type, slope, terrain ruggedness, distance to trails, distance to shoreline, distance to developed areas, and distance to freshwater sources. It is likely that other habitat characteristics also influence fox populations, but some of these will correlate highly with the variables we selected (e.g., distance to canyon bottoms would correlate strongly with our ruggedness index), and others are not currently available to measure (e.g., prey densities). This analysis should be viewed as preliminary, and we strongly recommend that future data from radio-collared foxes be used to evaluate and identify habitat features that influence fox densities or habitat selection.

We created data layers for each of the continuous variables (slope, terrain ruggedness, distance to trails, distance to shoreline, distance to developed areas, and distance to freshwater sources) in the following manner:

- Slope. We derived a slope layer from the USGS 30-m DEM. We chose to create a slope layer in degrees.
- Ruggedness. We created a Ruggedness raster layer using an Avenue script created and provided by Mark Sappington (National Park Service) and Kathy Longshore (U.S.

Geological Survey). This measure provides an index of ruggedness which ranges from 0 to 1, with 0 representing completely flat terrain and 1 representing the most rugged terrain. We used the USGS 30-m DEM as the basis for the algorithm, after converting its elevation values from feet to meters, and used a 90x90-m moving window to calculate ruggedness.

- Distance to shoreline. We created a raster layer of the distance-to-shoreline using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to trails. We created a raster layer of the distance to trails using the Distance ->Straight Line tool provided in the Spatial Analyst extension. The trails data layer was provided by the National Park Service.
- Distance to developed. We created a raster layer of the distance to developed areas using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to freshwater. Because a map of freshwater sources on San Miguel is not currently available, we used the USGS hydrology layer as a surrogate. This layer represents drainages and ravines, which may be more likely to contain surface freshwater or runoff than other areas, but are not guaranteed to provide water.
- Vegetation. We used a vegetation layer created and provided by the National Park Service. We examined the composition of vegetation across the entire island, and attempted to reduce the number of vegetation classifications to represent major vegetation types. The original and newly created classifications are shown in Table A-1.

Table A-1. Vegetation classifications on San Miguel Island, as originally classified and as grouped for analysis.

Original Classification	Representation of Original Classification on Island (%)	Vegetation as Categorized for Analysis
Island grassland	34.8	Island grassland
Haplopappus scrub	29.9	*Haplopappus* scrub
Beach and coastal dune	14.7	Beach and coastal dune
Unstabilized dune	11.8	Unstabilized dune
Coastal sage scrub	3.3	Other
Canyons	3.2	Other
Coastal bluff, sea-cliff phase	1.4	Other
Coastal bluff, Coreopsis phase	0.8	Other

Habitat characteristics were determined from two separate sets of random points; one distributed over the entire island and one distributed on trapped areas only. Trapped areas were defined as all locations within a 600-m buffer of a trap, excluding open water and avoiding double-counting of overlap areas for grids or traps <1,200 m apart. The 600-m buffer distance, added to represent the effective trap area of each trap, is equal to 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, pers. comm.). The number of random points was chosen by first placing points along a systematic grid with 90-m spacing, to result in a density of 144 points/km^2, and then applying this density of points randomly to the island and the trapped area.

We used the Mann-Whitney test (Sokal and Rohlf 1995) to test whether continuous variables (slope, ruggedness, distance to trails, etc.) differed between the island and trapped areas. To compare the composition of vegetation types, we used a chi-square goodness of fit test (Fowler et al. 1998), to compare vegetation composition of the trapped area versus on the entire island. We also visually compared the distributions of habitat attributes on the island versus those on trapped areas.

Results and Discussion

1990s Trapping Protocol

During 1993-1998, foxes on San Miguel Island were trapped annually on three grids, with a total of 146 traps. Individual grid sizes were 7x7 traps (two grids) and 6x8 traps (one grid). Assuming a 600-m effective trap radius, the three grids collectively sampled approximately 49% of the island.

Habitat sampled by the 1990s protocol is less steep and less rugged than island-wide habitat (Table A-2, Figures A-1 and A-2). However, although these differences are statistically significant, it is possible that they are not biologically meaningful in terms of sampling fox presence and abundance. The difference in median slopes is less than 1 degree, which may have limited influence on fox habitat use. Absolute differences in mean and median ruggedness values were also very small. Most terrain on San Miguel Island is relatively gentle, and the difference in ruggedness values between trapped and island-wide areas is small compared to the possible range of this index, in which a value of 0 represents completely flat terrain and 1 represents the most rugged terrain. It is likely that the lack of sampling near the shoreline (see below) causes trapped areas to have lower slope and ruggedness compared to the entire island but the extent of this difference, in itself, may have little influence on fox habitat use.

Areas trapped with the 1990s protocol are significantly farther from the shoreline than island-wide areas (Table A-2, Figure A-3). Although means and medians differ by <200 m, which may not be relevant given travel distances observed in foxes, the distribution of these distances indicates that areas within approximately 500 m of the shoreline are under-sampled by the trapping grids (Figure A-3). This may have relevance to trapping results, as foxes living along the shoreline would have reduced probability of capture.

Areas sampled with the 1990s protocol are closer to trails, developed areas, and freshwater than are island-wide random points (Table A-2, Figures A-4, A-5, and A-6). Distance to developed areas is greatly skewed, with distances >2,500 m not sampled by trapping protocols. The difference in distance to trails is less pronounced, with means and medians differing by <100 m. The impacts of trails and developed areas on fox density and habitat use are unknown, but trap proximity to these features may have relevance if foxes select or avoid areas near trails or developed areas. Differences between island-wide and trapped areas in distance to freshwater differ by <150 m, suggesting that this difference may not have biological relevance, but the fact that a small portion of the island, >1,500 m from this surrogate for freshwater, was not sampled with this trapping protocol may have relevance (Figure A-6).

The 1990s trapping protocol samples each of the five categories used in this analysis but it does not sample them in proportion to their availability on the islands (Chi-square = 97.89, df = 3, p <0.01; Figure A-7). This is likely caused primarily by over-sampling grassland vegetation, and under-sampling beach and coastal dunes as well as unstabilized dunes.

Table A-2. Comparison of habitat attributes on island (n = 4,560 random points) versus in areas trapped areas with 1990s Protocol (n = 2,249 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	8.17 (7.08)	7.45 (6.75)	5.82	5.49	-3.53	<0.001
Ruggedness Index	0.0018 (0.0045)	0.0014 (0.0034)	0.0005	0.0004	-5.49	<0.001
Dist. to Shore (m)	672.15 (428.97)	816.90 (407.73)	617.74	794.29	-13.89	<0.001
Dist. to Trails (m)	543.97 (411.78)	478.50 (369.20)	465.73	408.04	-5.51	<0.001
Dist. to Developed (m)	1718.84 (896.93)	1179.71 (561.00)	1651.09	1152.56	-23.32	<0.001
Dist. to Freshwater (m)	444.18 (427.87)	319.60 (264.25)	296.98	234.31	-9.663	<0.001

2006 Trapping Protocol

In 2006, foxes on San Miguel were trapped in four grids, each with the dimension of 6x3 traps, for a total of 72 traps. Each grid was set along an east-west trail, with the middle line of six traps placed along a trail. Assuming a 600-m effective trap radius, the four grids collectively sample approximately 37% of the island.

In terms of habitat representation, this protocol exhibits the same general pattern as the 1990s protocol, in that this protocol samples habitat with lower slope and ruggedness than island-wide areas, and that sampled areas are farther from the shore, and closer to trails, developed areas, and freshwater than are island-wide areas (Table A-3, Figures A-1─A-6). As discussed above, some of these statistical differences may not have biological differences. For example, small absolute differences in slope and ruggedness may not have an influence on fox habitat use patterns. However, of the four protocols included in this analysis, areas sampled with this protocol differ the most from the island in some measures; this protocol measures areas farthest from the shore, and closest to trails, developed areas, and freshwater in comparison to island-wide areas. The finding that this scenario is biased towards trails is not surprising, since the center line of traps in the grids was purposely placed on trails. This may produce a bias if foxes are more likely to move along trails as compared to nearby non-trail areas.

Grids trapped in 2006 sample all five of the vegetation categories used in this analysis but do not represent them in proportion to expected distributions based on island-wide vegetation composition (Figure A-8; Chi-square = 293.32, df = 3, p<0.01). This is likely due primarily to over-sampling grasslands and under-sampling beach and coastal dune and unstabilized dune areas.

Table A-3. Comparison of habitat attributes on island (n = 4,560 random points) versus in areas trapped with 2006 Protocol (n = 1,689 random points).

Habitat Measure	Island Mean (sd)	Trapped Area Mean (sd)	Island Median	Trapped Area Median	*Z*	*p*
Slope (degrees)	8.17 (7.08)	6.96 (6.14)	5.82	5.239	-4.86	<0.001
Ruggedness Index	0.0018 (0.0045)	0.0014 (0.0036)	0.0005	0.0003	-7.69	<0.001
Dist. to Shore (m)	672.15 (428.97)	971.01 (396.95)	617.74	990.46	-24.34	<0.001
Dist. to Trails (m)	543.97 (411.78)	339.46 (219.21)	465.73	330.00	-16.06	<0.001
Dist. to Developed (m)	1718.84 (896.93)	1588.58 (783.22)	1651.09	1606.05	-4.13	<0.001
Dist. to Freshwater (m)	444.18 (427.87)	275.76 (201.01)	296.98	218.40	-11.87	<0.001

Scenario B

Assuming a 600-m effective trap radius, Scenario B samples approximately 54% of the island. When compared to island-wide areas, this scenario also samples areas with lower slope and ruggedness, and tended to sample areas farther from the shore and closer to trails (Table A-4, Figures A1, A-2, A-3, and A-4). As discussed in relation to the 1990s and 2006 protocols, these statistical differences may not have biological relevance, as the absolute differences are relatively small in relation to the scale of measurement (slope and ruggedness) or in relation to fox movement patterns (distance to shore and trails). However, as with the other trapping protocols, the fact that areas close to the shore are under-sampled may bias trapping results if fox density is different near the shore than in other areas. Areas sampled with this scenario did not differ from island-wide areas in distance to developed areas or to freshwater.

Proposed trapping Scenario B samples all five vegetation categories used in this analysis but does not sample them in proportion to their availability on the island (Figure A-9; Chi-square = 57.07, df = 3, p<0.01). Visually, this trapping scenario appears to represent most vegetation categories fairly well, but the observed statistical difference is most likely due to over-sampling island grasslands, and under-sampling unstabilized dunes.

Table A-4. Comparison of habitat attributes on island (n = 4,560 random points) versus in areas trapped with proposed trapping Scenario B (n = 2,458 random points).

Habitat Measure	Island Mean (sd)	Trapped Area Mean (sd)	Island Median	Trapped Area Median	*Z*	*p*
Slope (degrees)	8.17 (7.08)	6.83 (5.89)	5.82	5.01	-6.70	<0.001
Ruggedness Index	0.0018 (0.0045)	0.0013 (0.0033)	0.0005	0.0004	-5.38	<0.001
Dist. to Shore (m)	672.15 (428.97)	780.63 (392.64)	617.74	768.38	-11.54	<0.001
Dist. to Trails (m)	543.97 (411.78)	395.02 (297.24)	465.73	335.41	-13.29	<0.001
Dist. to Developed (m)	1718.84 (896.93)	1740.38 (965.76)	1651.09	1838.46	-1.01	3.13
Dist. to Freshwater (m)	444.18 (427.87)	434.31 (370.77)	296.98	313.21	-1.77	0.08

Scenario C

Assuming a 600-m effective trap radius, Scenario C samples approximately 51% of the island. As with the three other trapping protocols included in this analysis, this scenario also samples areas with lower slope and ruggedness (Table A-5, Figures A-1 and A-2). This scenario also tended to sample areas farther from the shore and closer to trails, developed areas, and freshwater (Table A-5, Figures A-3, A-4, A-5, and A-6). In all cases, however, median and mean distances of sampled areas differed from island-wide areas by <150 m, which may not have relevance in relation to distances moved by foxes. Areas sampled with this scenario differed from island-wide areas the least in terms of ruggedness and distance to the shore. However, areas close to the shore remain under-sampled.

Proposed trapping Scenario C samples all five vegetation categories used in this analysis but does not sample them in proportion to their availability on the island (Chi-square = 117.99, df=3, p<0.01). This statistical difference is likely due to over-sampling of island grassland and *Haplopappus* scrub, and under-sampling of unstabilized dunes and beach and coastal dunes (Figure A-10).

Conclusions

All four trapping scenarios included in this analysis 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, since 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 above, 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 likely 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 towards areas near trails, which is not surprising since 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 the may provide valuable resources such as denning sites or foraging areas.

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. 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 is similar to Scenario B except for using slightly larger grids, would sample the island more effectively than Scenario B.

Table A-5. Comparison of habitat attributes on island (n = 4,560 random points) versus in areas trapped with proposed trapping Scenario C (n = 2,324 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	8.17 (7.08)	7.38 (6.38)	5.82	5.44	-3.76	<0.001
Ruggedness Index	0.0018 (0.0045)	0.0015 0.0036)	0.0005	0.0004	-4.42	<0.001
Dist. to Shore (m)	672.15 (428.97)	709.00 (362.74)	617.74	692.60	-5.52	<0.001
Dist. to Trails (m)	543.97 (411.78)	444.83 (359.61)	465.73	349.86	-9.18	<0.001
Dist. to Developed (m)	1718.84 (896.93)	1589.42 (902.86)	1651.09	1501.49	-5.11	<0.001
Dist. to Freshwater (m)	444.18 (427.87)	394.62 (374.87)	296.98	258.07	-3.82	<0.001

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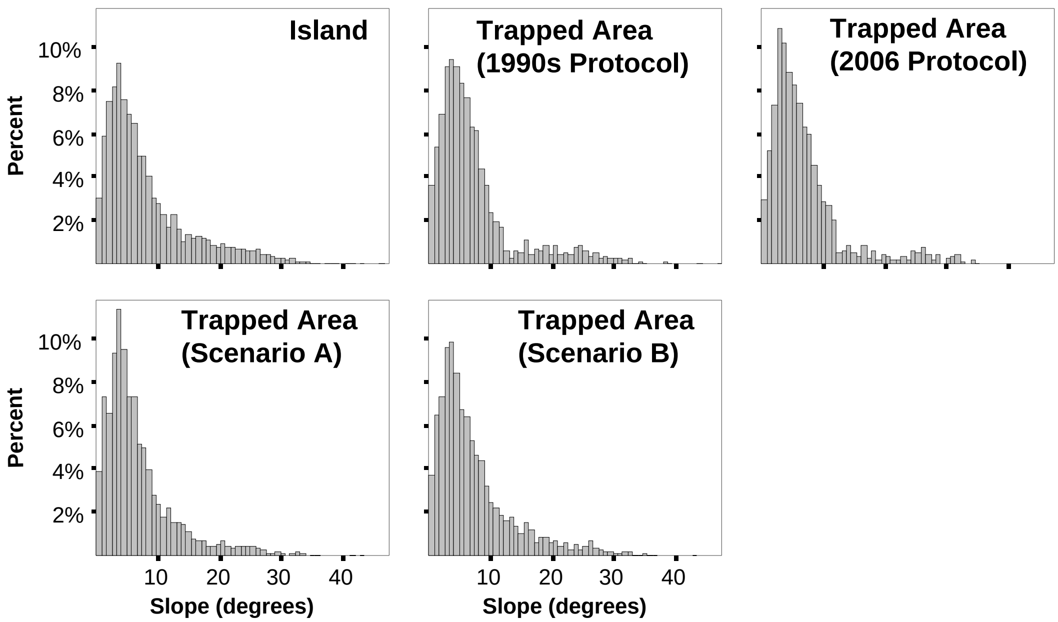

Figure A-1. Distribution of slope (as percent of random points) on San Miguel Island versus in areas trapped with four trapping scenarios (1990s Protocol, 2006 Protocol, Scenario B, and Scenario C).

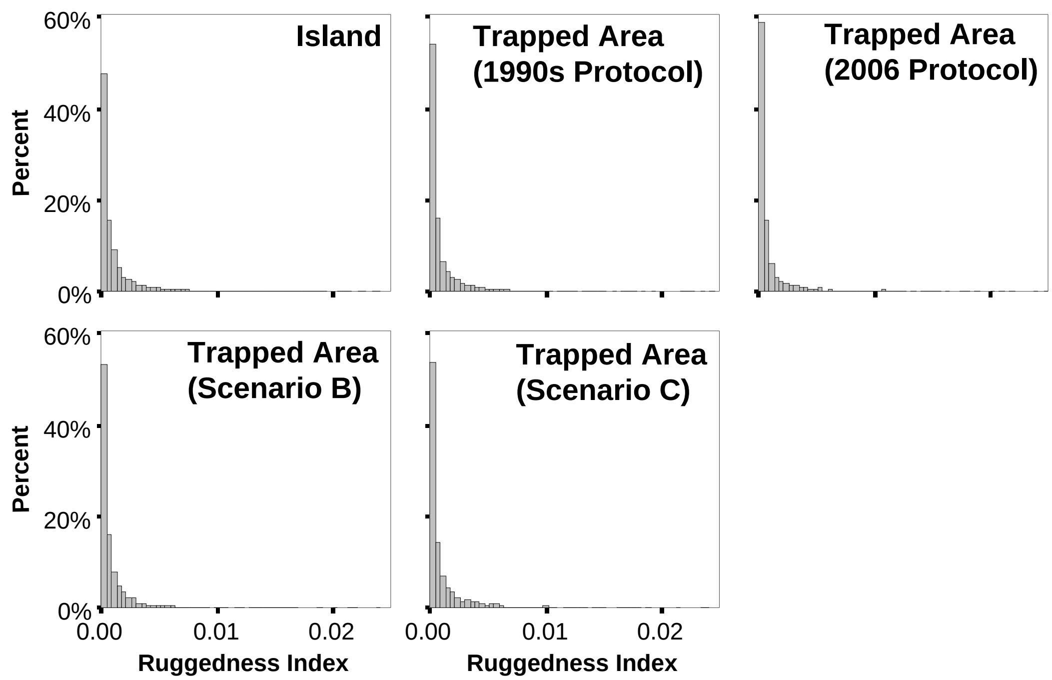

Figure A-2. Distribution of ruggedness (as percent of random points) on San Miguel Island versus in areas trapped with four trapping scenarios (1990s Protocol, 2006 Protocol, Scenario B, and Scenario C).

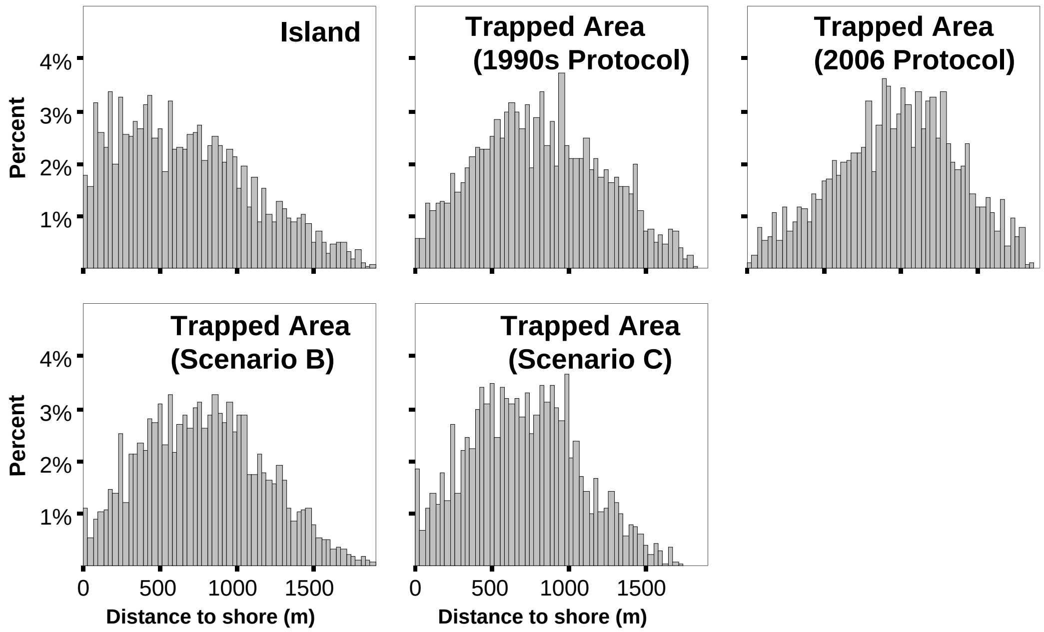

Figure A-3. Distribution of distance to the shore (in meters, as percent of random points) on San Miguel Island versus in areas trapped with four trapping scenarios (1990s Protocol, 2006 Protocol, Scenario B, and Scenario C).

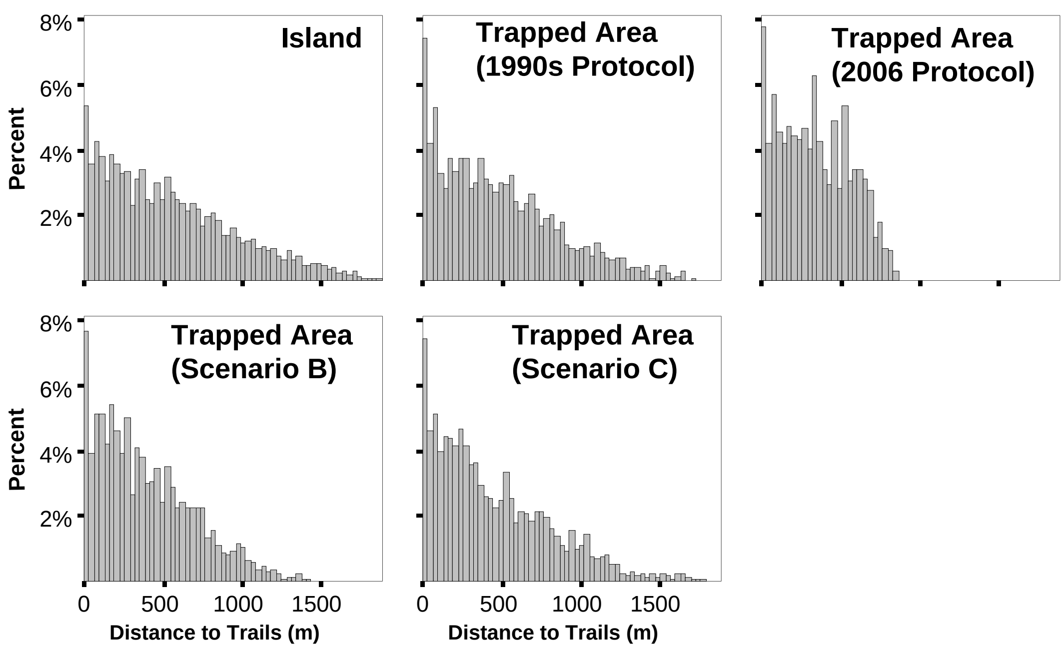

Figure A-4. Distribution of distance to trails (in meters, as percent of random points) on San Miguel Island versus in areas trapped with four trapping scenarios (1990s Protocol, 2006 Protocol, Scenario B, and Scenario C).

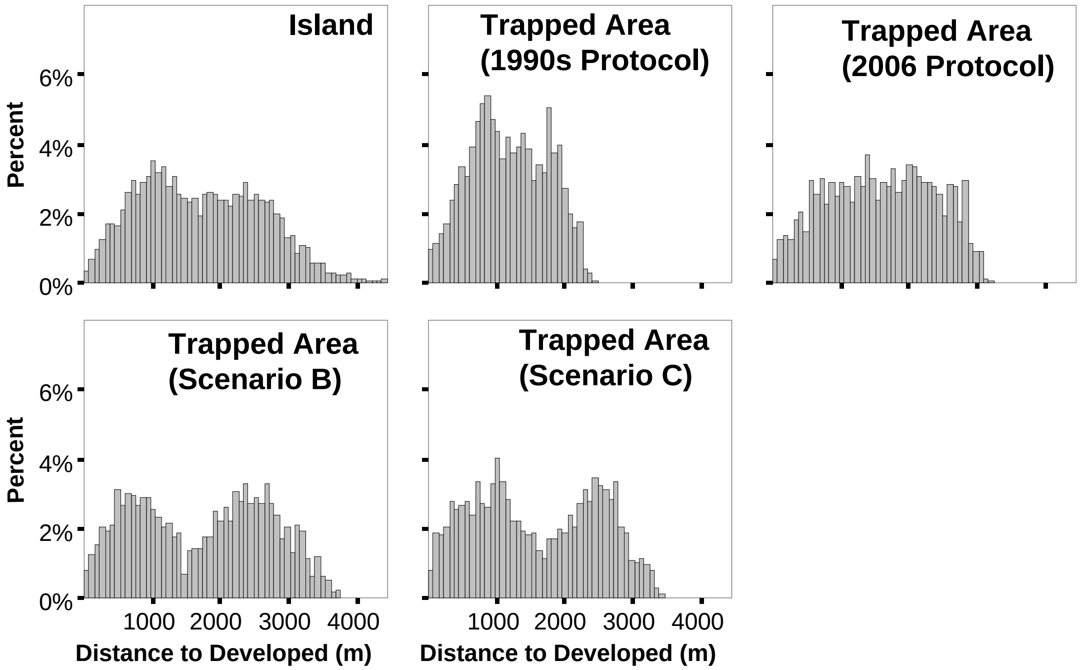

Figure A-5. Distribution of distance to developed areas (in meters, as percent of random points) on San Miguel Island versus in areas trapped with four trapping scenarios (1990s Protocol, 2006 Protocol, Scenario B, and Scenario C).

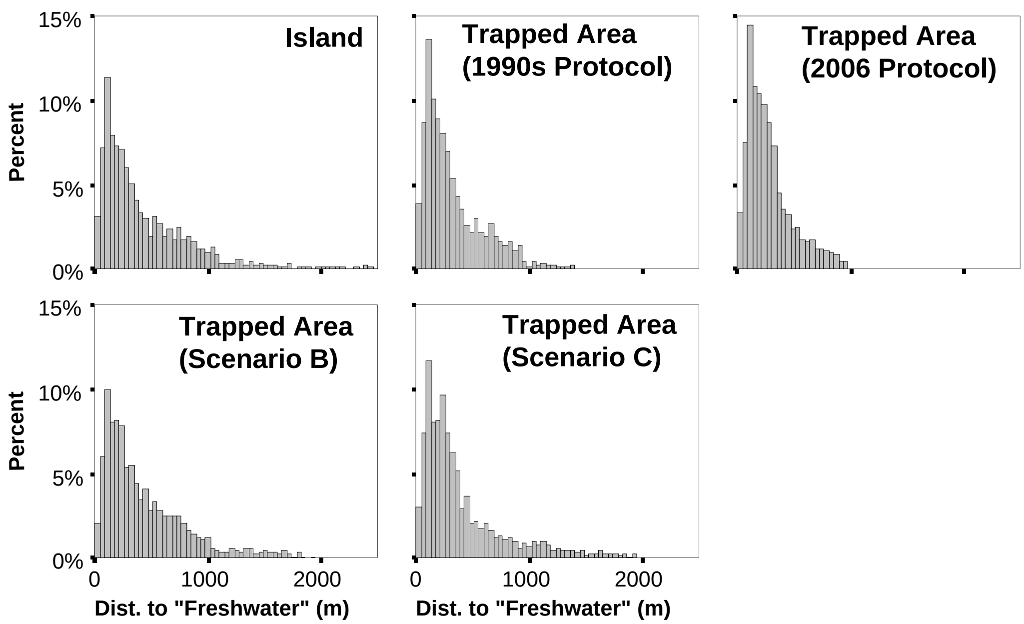

Figure A-6. Distribution of distance to freshwater (in meters, as percent of random points) on San Miguel Island versus in areas trapped with four trapping scenarios (1990s Protocol, 2006 Protocol, Scenario B, and Scenario C).

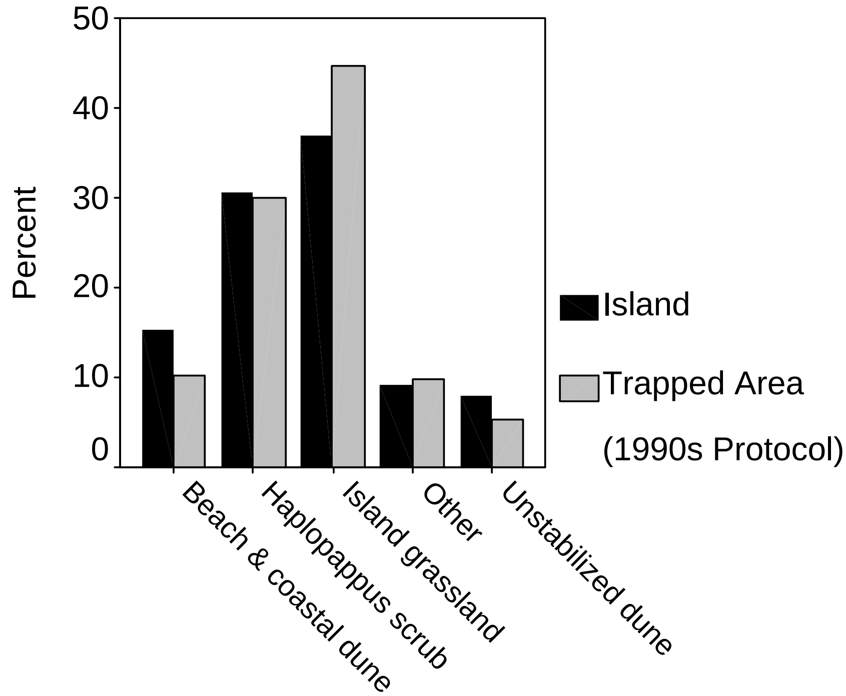

Figure A-7. Distribution of vegetation types (as percent of random points) on San Miguel Island versus areas trapped with the 1990s Protocol.

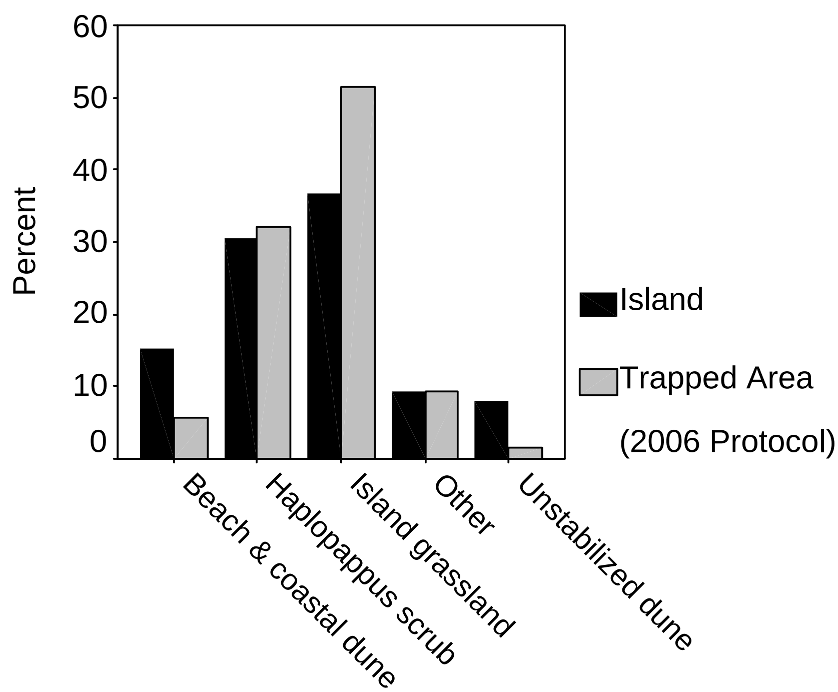

Figure A-8. Distribution of vegetation types (as percent of random points) on San Miguel Island versus areas trapped with the 2006 Protocol.

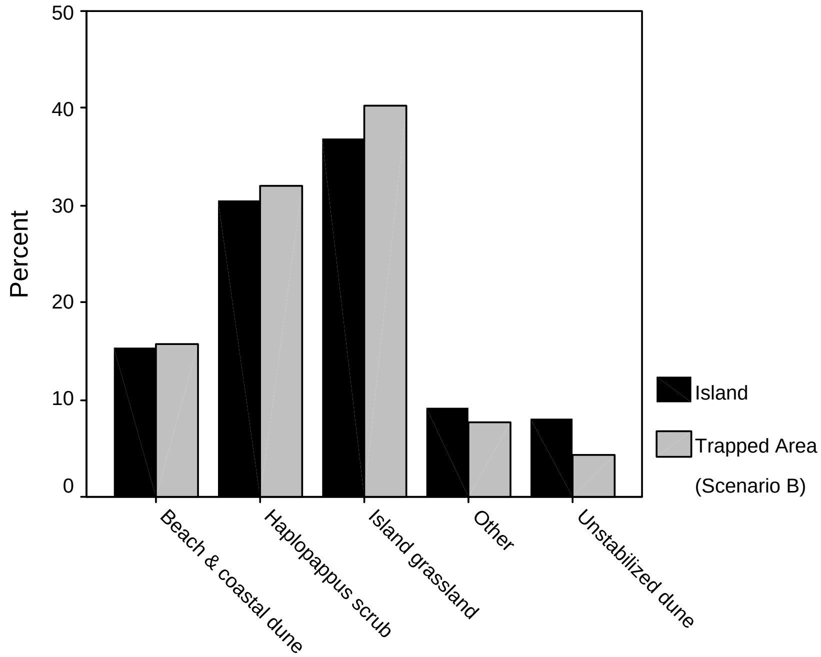

Figure A-9. Distribution of vegetation types (as percent of random points) on San Miguel Island versus areas trapped with Scenario B.

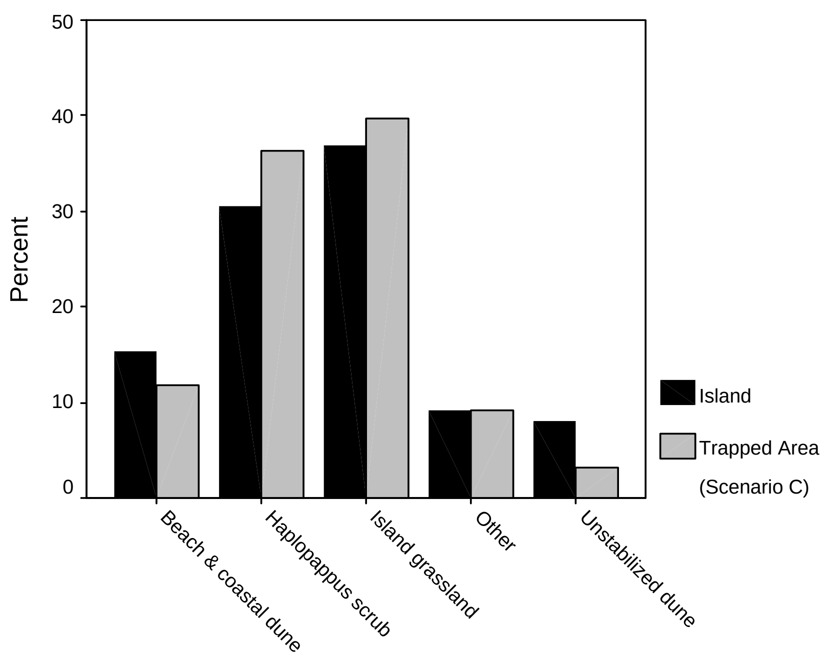

Figure A-10. Distribution of vegetation types (as percent of random points) on San Miguel Island versus areas trapped with Scenario C.

Appendix B

Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on San Nicolas Island

Introduction

This representation analysis examines how well existing and proposed trapping protocols represent habitat variation on San Nicolas Island. The goal of evaluating existing protocols was to identify gaps in island representation that could be addressed in proposed trapping scenarios, and to provide a baseline comparison with which to evaluate proposed scenarios. This information is intended to provide managers with additional information on which to base decisions about trapping protocols. In addition, increased knowledge regarding habitat representation of each trapping scenario may help identify research needs relative to habitat use and selection.

Although three alternative trapping scenarios are proposed for San Nicolas Island in the main body of this report (Maps 5-5, 5-6, and 5-7), we only conducted representation analyses on two (Scenarios B and C). It is assumed that Scenario A would effectively sample the island, because the approach distributes and shifts traps widely across the island.

Methods

We identified habitat variables currently available as GIS coverages or that could be created from existing GIS coverages, and for which we have empirical evidence or biological rationale to suspect that they may influence island fox habitat quality or population dynamics. Although we can not know or measure all habitat characteristics important to island foxes, we strived to maximize representation of the following habitat attributes that we can measure: vegetation type, slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources. It is likely that other habitat characteristics also influence fox populations, but some of these will correlate highly with the variables we selected (e.g., distance to canyon bottoms would correlate strongly with our ruggedness index), and others are not currently available to measure (e.g., cat densities or prey densities). This analysis should be viewed as preliminary, and we strongly recommend that future data from radio-collared foxes be used to evaluate and identify habitat features that influence fox densities or habitat selection.

We created data layers for each of the continuous variables (slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources) in the following manner:

- <u>Slope</u>. We derived a slope layer from the USGS 30-m DEM. We chose to create a slope layer in degrees.

- Ruggedness. We created a Ruggedness raster layer using an Avenue script created and provided by Mark Sappington (National Park Service) and Kathy Longshore (U.S. Geological Survey). This measure provides an index of ruggedness which ranges from 0 to 1, with 0 representing completely flat terrain and 1 representing the most rugged terrain. We used the USGS 30-m DEM as the basis for the algorithm, after converting its elevation values from feet to meters, and used a 90x90-m moving window to calculate ruggedness.
- Distance to shoreline. We created a raster layer of the distance-to-shoreline using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to paved road. We created a raster layer of the distance to paved roads using the Distance ->Straight Line tool provided in the Spatial Analyst extension. The paved road data layer was provided by Grace Smith, U.S. Navy.
- Distance to developed. We created a raster layer of the distance to developed areas using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to freshwater. Because a map of freshwater sources on San Nicolas Island was not available, we used riparian and vernal pool vegetation as a surrogate for freshwater. These areas are not guaranteed to provide surface freshwater year-round, but could have a higher probability of providing this resource than other areas on the island.
- Vegetation. We used a vegetation layer provided by Grace Smith, U.S. Navy. We examined the composition of vegetation across the entire island, and attempted to reduce the number of vegetation classifications to represent major vegetation types. The original and newly created classifications are shown in Table B-1.

Table B-1. Vegetation classifications on San Nicolas Island, as originally classified and as grouped for analysis.

Original Classification	**Representation of Original Classification on Island (%)**	**Vegetation as Categorized for Analysis**
Coastal scrub	42.1	Coastal scrub
Barren	24.3	Barren
Grassland	12.2	Grassland
Coreopsis	9.5	*Coreopsis*
Inland dune	5.5	Inland dune
Developed	2.3	(not included in trap area)
Beach	1.6	Other
Riparian	1.4	Other
Coastal dune	1.0	Other
Coastal marsh	0.1	Other
Lupine	<0.1	Other
Pine trees	<0.1	Other
Vernal pool	<0.1	Other

Habitat characteristics were determined from two separate sets of random points; one distributed over the entire island and one distributed on trapped areas only. Trapped areas were defined as all locations within a 600-m buffer of a trap, excluding open water and avoiding double-counting of overlap areas for grids or traps <1,200 m apart. The 600-m buffer distance, added to represent the effective trap area of each trap, is equal to 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, pers. comm.). The number of random points was chosen by first placing points along a systematic grid with 90-m spacing, to result in a density of 144 points/km^2, and then applying this density of points randomly to the island and the trapped area. For our evaluation of trapping scenarios, we randomly chose 5,000 of these points from the island as a comparison to trapped points.

We used the Mann-Whitney test (Sokal and Rohlf 1995) to test whether continuous variables (slope, ruggedness, distance to roads, etc.) differed between the island and trapped areas. To compare the composition of vegetation types, we used a chi-square goodness-of-fit test (Fowler et al. 1998), to compare vegetation composition of the trapped area versus island-wide areas. We also visually compared the distributions of habitat attributes on the island versus those on trapped areas.

Results and Discussion

Existing Trapping Protocols

Since 2000, island foxes on San Nicolas Island have been trapped annually in three trapping grids. Grids contain a total of 148 traps, with the following individual grid sizes: Skyline─5x10 traps, Tuft's─5x10 traps, Redeye─6x8 traps. Assuming a 600-m effective trap radius, the three grids collectively sample approximately 35% of the island (Map 5-1).

Trapped areas have significantly lower slope than the island, and examination of slope distribution on the island versus trapped areas indicates a tendency of the trapped areas to over-represent areas of gentle terrain with slopes of <10° (Table B-2, Figure B-1). However, this statistical significance may not necessarily represent biological significance, since mean and median slopes at island-wide points were only 1-2° steeper than trap-area points. It is possible that this slope difference, in itself, may have little or no influence on fox habitat use or density.

Trapped areas are also significantly less rugged than the overall island areas (Table B-2), and the distributions of ruggedness values in the island-wide and trapped points also suggests that trapped areas tend to over-sample the least rugged terrain on the island (Figure B-2). However, as in the case of slope, it is not known if this difference would have biological relevance to trapping results. The extent of this difference (0.003 versus 0.002) is extremely small compared to the range of the ruggedness index, which has a value of 0 for completely flat terrain and a value of 1 for extremely rugged terrain. These values suggest that both the island and trapped areas include mostly very gentle terrain.

Our analyses indicate that trapped areas are significantly farther from the shoreline than random points on the entire island (Table B-2). The distribution of this distance in trapped areas versus island-wide areas shows that areas close to the shore, particularly those <1,000 m from the shore, are under-represented in the current trapping protocols (Figure B-3). This may influence trapping results, because foxes living along the shore would have a reduced probability of being trapped, as 1,000 m exceeds the mean maximum distance moved as observed in existing trap data (V. Bakker, pers. comm.).

Areas currently trapped are located closer to paved roads and to developed areas than random points over the entire island (Table B-2, Figures B-4 and B-5). Although the absolute difference in these distances is not large (<200 m), it is possible that these differences may have biological significance. For example, density estimates may be influenced if, for example, foxes experience higher mortality near roads or if they are attracted to urban areas.

Trapped areas are also closer to freshwater sources, which were defined, on San Nicolas Island, as riparian or vernal pool vegetation (Table B-2). These areas are not guaranteed to provide surface freshwater year-round, but could have a higher probability of providing this resource than other areas on the island. Because the difference between median distances (a difference of about 90 meters) is small compared to daily fox movement distances, and the distributions of this measure in the two samples are somewhat similar (Figure B-6), it is likely that this difference may not have biological significance.

The current trapping protocol samples each of the 6 vegetation categories used in our analyses; however, the distribution of these categories is different in the trapped area than expected based on their distribution on the entire island (Chi-square = 659.768, df = 4, $p<0.01$). This appears to be due primarily to under-sampling of barren areas and *Coreopsis* vegetation, and over-sampling of coastal scrub and possibly inland dune areas (Figure B-7).

Table B-2. Comparison of habitat attributes on San Nicolas Island (n = 5,000 random points) versus area trapped with existing trapping protocol (n = 2,574 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	7.53 (6.21)	6.01 (5.24)	5.55	4.36	-10.92	<0.001
Ruggedness Index	0.015 (0.029)	0.009 (0.025)	0.003	0.002	-14.61	<0.001
Dist. to Shore (m)	1050.92 (693.88)	1456.13 (666.07)	959.50	1508.50	-23.50	<0.001
Dist. to Paved Roads (m)	572.98 (475.02)	386.47 (310.42)	442.00	314.00	-14.43	<0.001
Dist. to Developed (m)	580.20 (407.38)	447.00 (251.37)	505.00	425.00	-10.88	<0.001
Dist. to Freshwater (m)	875.25 (658.49)	760.66 (867.87)	738.00	674.00	-4.802	<0.001

Scenario B

Assuming a 600-m effective trap radius around each trap, Scenario B samples approximately 36% of San Nicolas Island (Map 5-6). Scenario B is similar to existing protocols in that sampled areas differ significantly from the island in continuous variables measured (Table B-3). As in the existing protocols, areas with low slope and ruggedness are over-sampled, but, as discussed in relation to existing protocols, the small absolute differences in these measures may not have biological relevance to fox habitat use (Figures B-1 and B-2). Sampled areas are also farther from the shore, and closer to roads, developed areas, and sources of freshwater than were random points on the island. It is not clear if differences in distance to roads, developed areas, and sources of freshwater have biological significance, however, since the absolute differences (when means and medians are examined) are <250 m (Table B-3, Figures B-4, B-5, and B-6). In terms of distance to the shore, this scenario also under-samples areas within 1000 meters of the shore, which could, as discussed above in relation to the existing protocol, cause bias in trap results if fox densities are different near the shore (Figure B-3).

In terms of vegetation sampled, this scenario provides an improvement over the existing protocol, because sampling includes more *Coreopsis* vegetation (Figures B-7 and B-8). However, this scenario still fails to represent all vegetation types in proportion to presence on the island (Chi-square = 518.32, df = 4, $p < 0.01$), most likely because it tends to over-sample Coastal Scrub and Grassland vegetation and under-sample Barren areas.

Table B-3. Comparison of habitat attributes on San Nicolas Island (n = 5,000 random points) versus area trapped with trapping Scenario B (n = 2,614 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	7.53 (6.21)	6.15 (5.24)	5.55	4.50	-9.34	<0.001
Ruggedness Index	0.015 (0.029)	0.001 (0.004)	0.003	0.0002	-48.63	<0.001
Dist. to Shore (m)	1050.92 (693.88)	1465.22 (682.01)	959.50	1593.50	-23.88	<0.001
Dist. to Paved Roads (m)	572.98 (475.02)	394.42 (323.55)	442.00	312.00	-14.09	<0.001
Dist. to Developed (m)	580.20 (407.38)	452.78 (300.81)	505.00	412.00	-11.57	<0.001
Dist. to Freshwater (m)	875.25 (658.49)	654.85 (465.93)	738.00	574.00	-12.13	<0.001

Scenario C

Assuming a 600-m effective trap radius around each trap, Scenario C samples approximately 39% of San Nicolas Island (Map5-7). Scenario C is similar to the existing protocol and Scenario B in that sampled areas differ significantly from the island in continuous variables measured (Table B-4). As discussed above, some of these statistical differences may not indicate biological differences. This scenario does, however, provide an improvement in that it more closely resembles the island in terms of distances to the shore, paved roads, developed areas, and sources of freshwater (Table B-4, Figures B-3, B-4, B-5, and B-6). It is similar to the existing protocol in terms of slopes measured, but differs more from the island in terms of ruggedness.

In terms of vegetation sampled, Scenario C provides better representation of vegetation than Scenario B or the existing protocol do, although a significant difference still exists between the island and trapped areas (Chi-square = 267.25, df = 4, p <0.01), with some under-sampling of *Coreopsis* and Barren areas, and over-sampling of Coastal Scrub and Grassland vegetation.

Table B-4. Comparison of habitat attributes on San Nicolas Island (n = 5,000 random points) versus area trapped with trapping Scenario C (n = 2,808 random points).

Habitat Measure	Island Mean (sd)	Trapped Area Mean (sd)	Island Median	Trapped Area Median	*Z*	*p*
Slope (degrees)	7.53 (6.21)	6.26 (5.25)	5.55	4.55	-10.92	<0.001
Ruggedness Index	0.015 (0.029)	0.002 (0.005)	0.003	0.0002	-45.83	<0.001
Dist. to Shore (m)	1050.92 (693.88)	1214.19 (753.48)	959.50	1100.50	-9.11	<0.001
Dist. to Paved Roads (m)	572.98 (475.02)	514.06 (431.29)	442.00	398.00	-4.05	<0.001
Dist. to Developed (m)	580.20 (407.38)	530.33 (387.41)	505.00	446.00	-5.47	<0.001
Dist. to Freshwater (m)	875.25 (658.49)	805.79 (572.21)	738.00	701.50	-2.96	0.003

Conclusions

The three scenarios examined in this appendix (existing trapping protocol, Scenario B, and Scenario C) all sample areas that differ statistically from random points on the island for all habitat measures examined. However, statistical differences do not necessarily indicate biologically relevant differences. For example, statistical differences were found in slope and ruggedness, with trapping areas representing areas with lower slope and ruggedness, but absolute differences were small and may not influence trapping results. Trapped areas also sampled areas closer to paved roads, developed areas, and sources of freshwater, but in all cases the actual differences were small relative to fox movement patterns so these differences may not bias trapping. It is possible, however, that small differences in distance to roads may influence trap results, if fox density differs near roads. In addition, under-sampling of areas close to the shore may bias trapping results if fox density is different close to the shore than in other areas. Scenario C most closely resembled the island in terms of distance to the shore and to roads, and in representation of vegetation categories, and overall provides a better representation of the island than the existing protocol or Scenario B, although differences do exist between Scenario C and island-wide areas. We suggest that future habitat selection studies should be conducted to examine if these differences might bias trap results. Proposed trapping Scenario A was not examined in this appendix because we assume that it will provide the best representation of habitat on San Nicolas Island, due to the extensive distribution and shifting of trap sites.

Literature Cited

Fowler, J., L. Cohen, and P. Jarvis. 1998. Practical Statistics for Field Biology. 2nd ed. John Wiley and Sons, New York, NY. 259pp.

Sokal, R.R., and F.J. Rohlf. 1995. Biometry: The Principles and Practices of Statistics in Biological Research. 3rd ed.. W.H. Freeman and Company, New York, NY. 887pp.

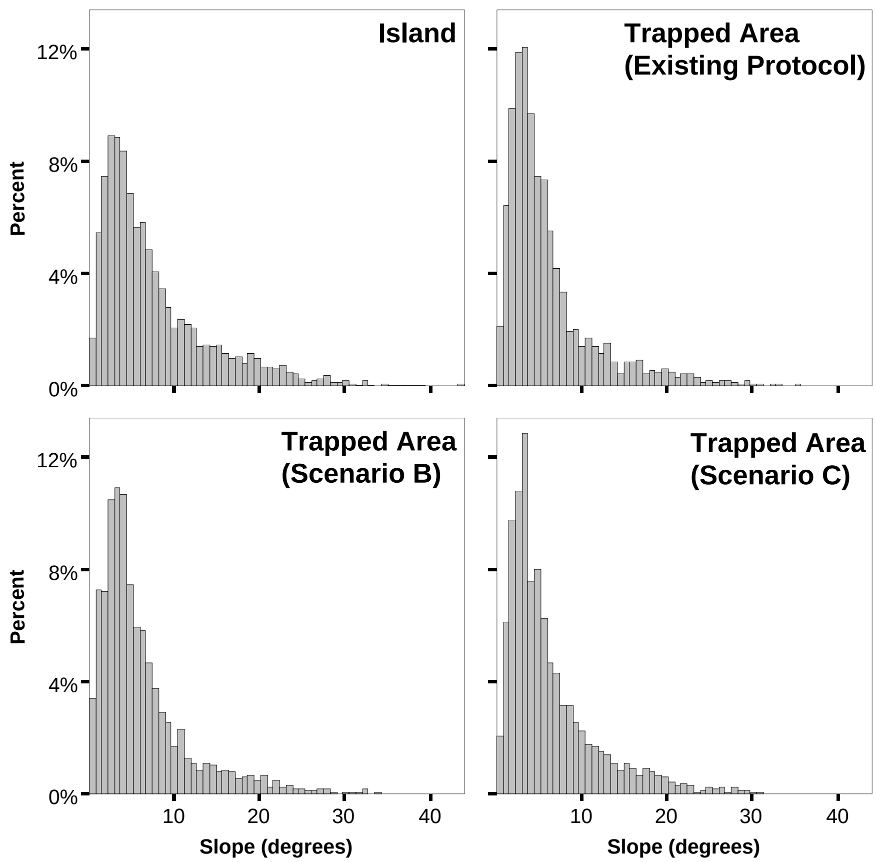

Figure B-1. Distribution of slope (as percent of total random points) on San Nicolas Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario B, and Scenario C).

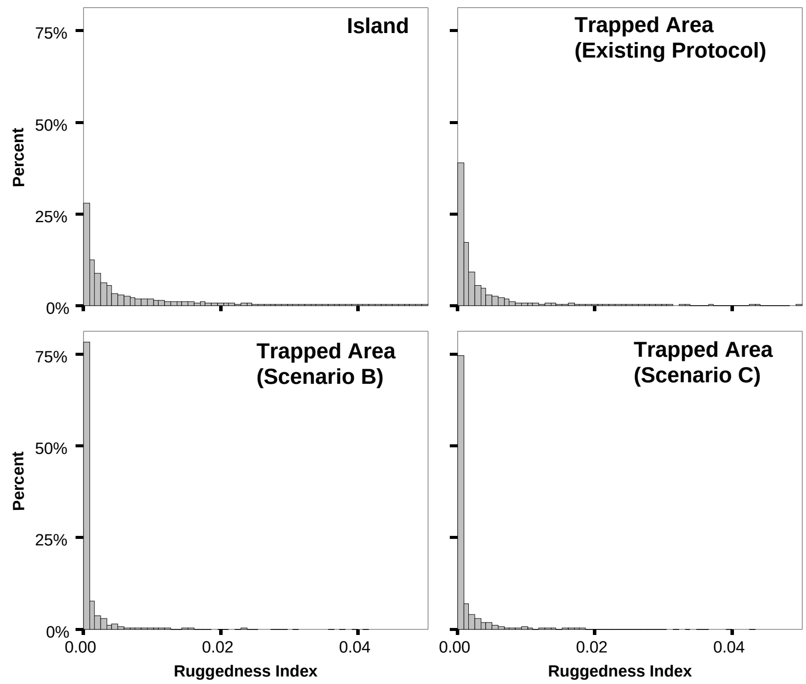

Figure B-2. Distribution of ruggedness index (as percent of total random points) on San Nicolas Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario B, and Scenario C).

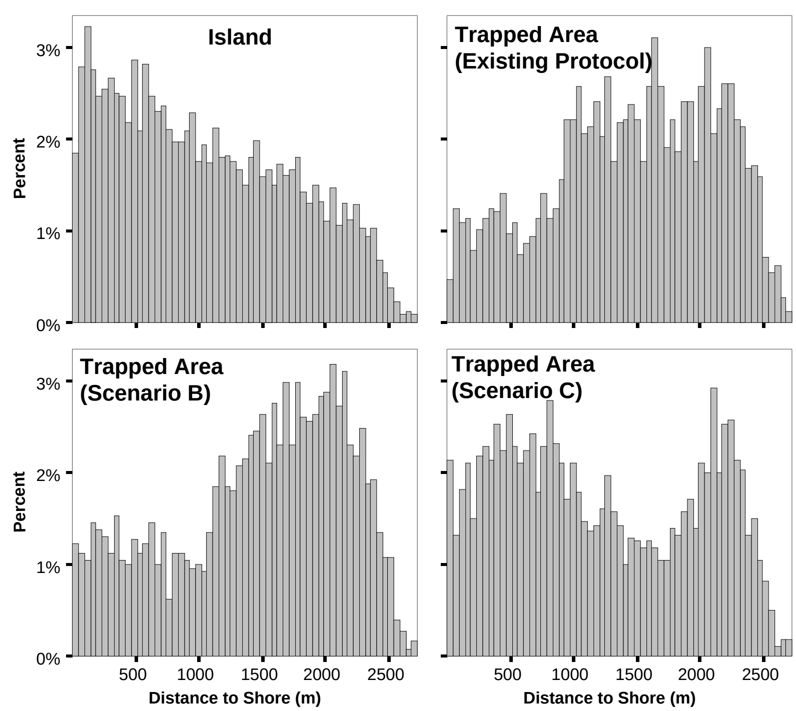

Figure B-3. Distribution of distance to shore (as percent of total random points) on San Nicolas Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario B, and Scenario C).

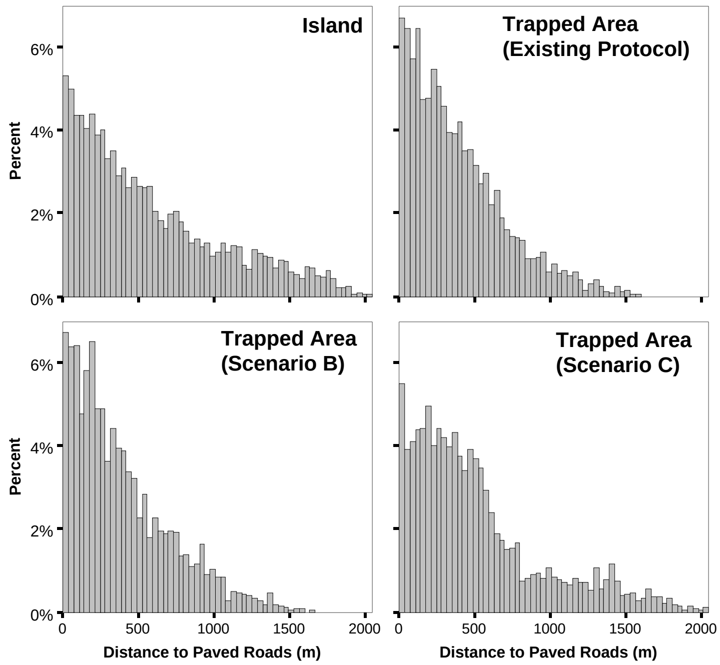

Figure B-4. Distribution of distance to paved roads (as percent of total random points) on San Nicolas Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario B, and Scenario C).

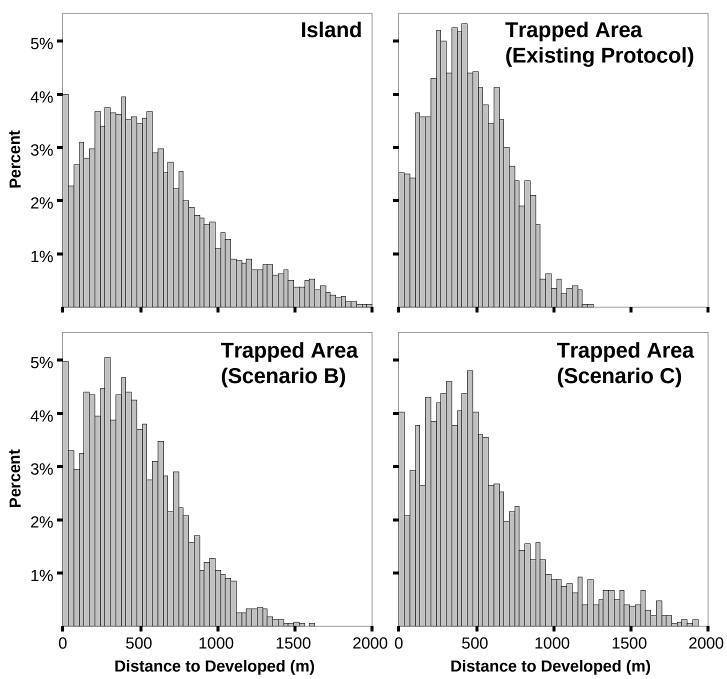

Figure B-5. Distribution of distance to developed areas (as percent of total random points) on San Nicolas Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario B, and Scenario C).

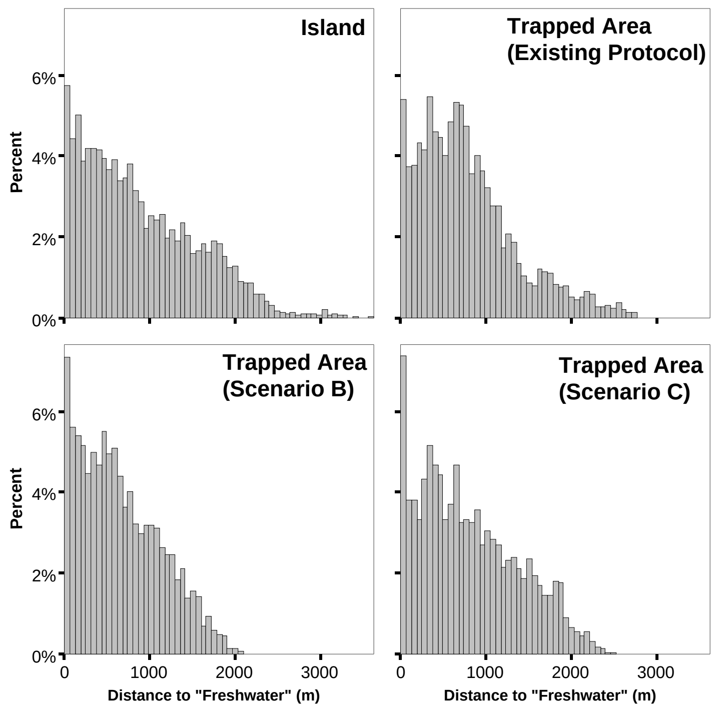

Figure B-6. Distribution of distance to freshwater (as percent of total random points) on San Nicolas Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario B, and Scenario C).

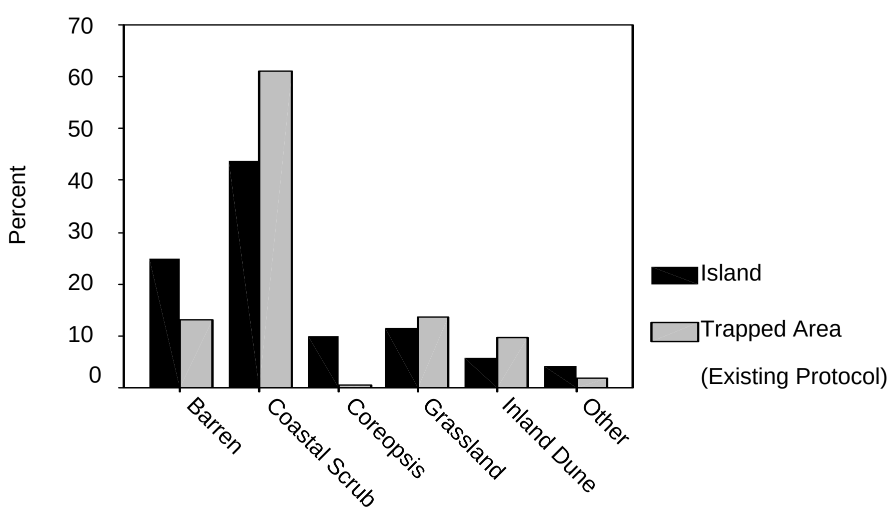

Figure B-7. Representation of vegetation types on San Nicolas Island versus area trapped with current protocol, based on classification at random points.

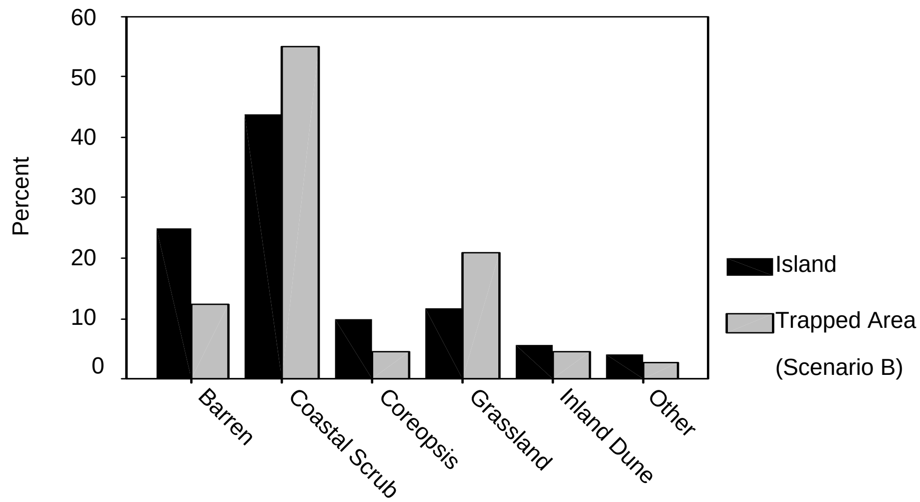

Figure B-8. Representation of vegetation types on San Nicolas Island versus area trapped with Scenario B, based on classification at random points.

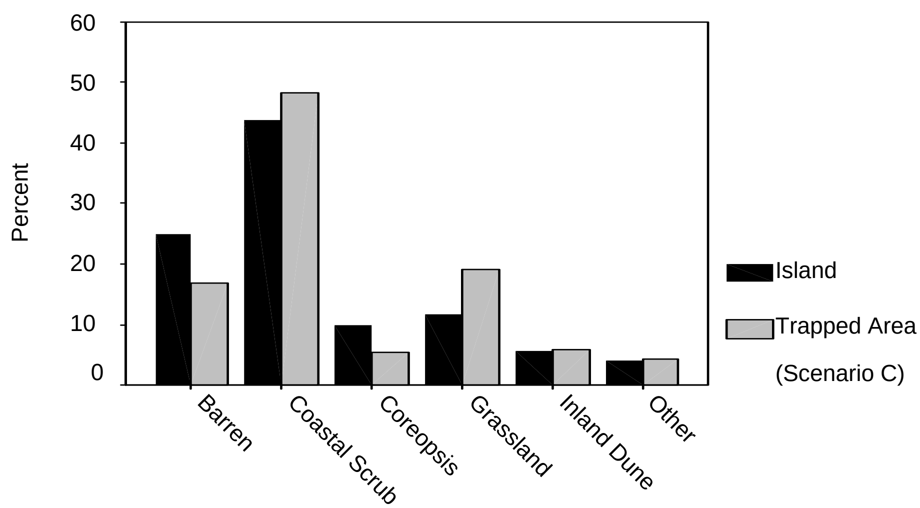

Figure B-9. Representation of vegetation types on San Nicolas Island versus area trapped with Scenario A, based on classification at random points.

Appendix C

Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on Santa Catalina Island

Introduction

This representation analysis examines how well existing and recommended trapping protocols represent habitat variation on Santa Catalina Island. The goal of evaluating existing protocols was to identify gaps in island representation that could be addressed in proposed trapping scenarios, and to provide a baseline comparison with which to evaluate proposed scenarios. This information is intended to provide managers with additional information on which to base decisions about trapping protocols. In addition, increased knowledge regarding habitat representation of each trapping scenario may help identify research needs relative to habitat use and selection.

Methods

We identified habitat variables currently available as GIS coverages or that could be created from existing GIS coverages, and for which we have empirical evidence or biological rationale to suspect that they may influence island fox habitat quality or population dynamics. Although we can not know or measure all habitat characteristics important to island foxes, we strived to maximize representation of the following habitat attributes that we can measure: vegetation type, slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources. It is likely that other habitat characteristics also influence fox populations, but some of these will correlate highly with the variables we selected (e.g., distance to canyon bottoms would correlate strongly with our ruggedness index), and others are not currently available to measure (e.g., cat densities or prey densities). This analysis should be viewed as preliminary, and we strongly recommend that future data from radio-collared foxes be used to evaluate and identify habitat features that influence fox densities or habitat selection.

We created data layers for each of the continuous variables (slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources) in the following manner:

- Slope. We derived a slope layer from the USGS 30-m DEM. We chose to create a slope layer in degrees.
- Ruggedness. We created a Ruggedness raster layer using an Avenue script created and provided by Mark Sappington (National Park Service) and Kathy Longshore (U.S. Geological Survey). This measure provides an index of ruggedness which ranges from 0 to 1, with 0 representing completely flat terrain and 1 representing the most rugged

terrain. We used the USGS 30-m DEM as the basis for the algorithm, after converting its elevation values from feet to meters, and used a 90x90-m moving window to calculate ruggedness.

- Distance to shoreline. We created a raster layer of the distance-to-shoreline using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to roads. We created a raster layer of the distance to roads using the Distance ->Straight Line tool provided in the Spatial Analyst extension. The road data layer was provided by the Catalina Island Conservancy.
- Distance to developed. We created a raster layer of the distance to developed areas using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to freshwater. Because a map of freshwater sources on Santa Catalina Island was not available, we used the following vegetation types as a surrogate for freshwater: riparian herbaceous, southern riparian woodland, vernal pools, and reservoirs. These areas may be more likely to contain surface freshwater or runoff than other areas, but are not guaranteed to provide water.
- Vegetation. We used a vegetation layer created and provided by the Catalina Island Conservancy. We examined the composition of vegetation across the entire island, and attempted to reduce the number of vegetation classifications to represent major vegetation types. The original and newly created classifications are shown in Table C-1.

Table C-1. Vegetation classifications on Santa Catalina Island, as originally classified and as grouped for analysis.

Original Classification	**Representation of Original Classification on Island (%)**	**Vegetation as Categorized for Analysis**
Coastal Sage Scrub	38.736	Coastal Sage Scrub
Island Chaparral	30.450	Island Chaparral
Grassland	18.940	Grassland
Bare	9.019	Bare
Island Woodland	0.518	Other
Non-Native Herbaceous	0.514	Other
Southern Riparian Woodland	0.406	Other
Non-Native Scrub	0.338	Other
Southern Beach and Dune	0.296	Other
Non-Native Woodland	0.292	Other
Coastal Bluff Scrub	0.172	Other
Bare StreamBed	0.129	Other
Vernal Ponds & Reservoirs	0.111	Other
Riparian Herbaceous	0.061	Other
Coastal Marsh	0.008	Other
Maritime Cactus Scrub	0.007	Other
Mule Fat Scrub	0.003	Other

Habitat characteristics were determined from two separate sets of random points; one distributed over the entire island and one distributed on trapped areas only. Trapped areas were defined as all locations within a 600-m buffer of a trap, excluding open water and avoiding double-counting of overlap areas for grids or traps <1,200 m apart. The 600-m buffer distance, added to represent the effective trap area of each trap, is equal to 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, pers. comm.). The number of random points was chosen by first placing points along a systematic grid with 90-m spacing, to result in a density of 144 points/km^2, and then applying this density of points randomly to the island and the trapped area. For our evaluation of trapping scenarios on the East End, we randomly chose 5.000 points from the island and from the trapped points, to reduce this large dataset for analysis. The West End of the island does not include paved roads or known sources of freshwater; therefore representation of these variables was not evaluated for the West End.

We used the Mann-Whitney test (Sokal and Rohlf 1995) to test whether continuous variables (slope, ruggedness, distance to roads, etc.) differed between the island and trapped areas. To compare the composition of vegetation types, we used a chi-square goodness of fit test (Fowler et al. 1998), to compare vegetation composition of the trapped area versus on the entire island. We also visually compared the distributions of habitat attributes on the island versus those on trapped areas.

Results and Discussion

Existing Trapping Protocols

<u>East End</u>

Assuming a 600-m effective trap radius around each trap, current trapping protocols sample approximately 79% of Santa Catalina Island's East End (Map 6-1). Even given this extensive trapping effort, sampled areas still differed statistically from island-wide areas in some habitat measures. Trapped areas had lower slope and ruggedness than random points on the East End (Table C-2, Figures C-1 and C-2). However, it is unknown if these statistical differences in these two measures, alone, have biological meaning. The difference in mean and median slopes was approximately 1 degree, which may not have relevance to fox habitat selection. In addition, the difference in median ruggedness (0.0067 versus 0.0059) was extremely small compared to the range of the ruggedness index, which has a value of 0 for completely flat terrain and a value of 1 for extremely rugged terrain.

Trapped areas were significantly farther from the shoreline than were random points on the East End (Table C-2, Figure C-3). The mean and median values differed, however, by <200 m, which may not have biological relevance if compared to island fox movement rates. Nonetheless, the distribution of this distance among random points in trapped areas versus those on the entire East End indicates that areas close to the shore, particularly those <1,000 m from the shore, are under-represented in the current trapping protocols (Figure C-3). This may influence trapping results, because foxes living along the shore would have a reduced probability of capture, as 1,000 m exceeds the mean maximum distance moved observed in previous trapping sessions (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 was 600 m; V. Bakker, pers.

comm.). Future habitat selection studies could shed light on whether this would bias trapping results high or low, by determining if areas close to the shore are selected or avoided.

Trapped areas were closer to vegetation surrogates for freshwater than random points distributed on the East End (Table C-2, Figure 6). However, means and medians differed by <150 m, suggesting that this difference may not have biological relevance. Again, habitat selection studies could shed light on this influence by determining if foxes select or avoid these areas.

Trapped and island-wide (East End) areas did not differ in terms of distance to roads or to developed areas (Table C-2, Figures C-4 and C-5). Trapping on the East End appeared to represent the five reclassified vegetation categories fairly closely (Figure C-7); however, there was a statistical difference between trapped areas and random points on the East End, with trapped areas slightly under-representing Barren areas, and slightly over-representing Grassland and Island Chaparral vegetation (Chi-square = 37.72, df = 4, p<0.01).

Table C-2. Comparison of habitat attributes on Santa Catalina Island's East End (n = 5000 random points) versus areas trapped with existing protocol on the East End (n = 5000 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***P***
Slope (degrees)	18.70 (9.00)	17.68 (8.37)	17.69	16.63	-5.08	<0.001
Ruggedness Index	0.0112 (0.0126)	0.0103 (0.0118)	0.0067	0.0059	-3.89	<0.001
Dist. to Shore (m)	1758.63 (1223.9)	1931.62 (1195.9)	1532.94	1725.85	-8.12	<0.001
Dist. to Paved Roads (m)	2914.85 (2255.9)	2906.03 (2206.9)	2336.92	2411.45	-0.10	0.92
Dist. to Developed (m)	1299.38 (878.39)	1321.05 (850.51)	1168.46	1189.26	-1.89	0.06
Dist. to Freshwater (m)	996.95 (690.17)	866.29 (588.74)	849.32	752.39	-8.14	<0.001

<u>West End</u>

Assuming a 600-m effective trap radius around each trap, current trapping protocols sample approximately 84% of Santa Catalina Island's West End (Map 6-1). However, even with such an extensive trapping effort, trapped areas were statistically less steep and rugged than those sampled by random points on the West End (Table C-3, Figures C-8 and C-9). However, just as on the East End, it is unknown if these statistical differences in these two measures, alone, have biological meaning. The difference in mean and median slopes is <1°, which probably does not, by itself, have relevance to fox habitat selection. In addition, difference in ruggedness are extremely small compared to the range of the ruggedness index, which has a value of 0 for completely flat terrain and a value of 1 for extremely rugged terrain, suggesting that this statistical difference may not have biological relevance.

Trapped areas were significantly farther from the shoreline than were areas sampled by random points on the West End (Table C-3, Figure C-10). However, the mean and median values differed only by approximately 100 m, which may not have biological relevance if compared to island fox movement rates. Nevertheless, the distribution of this distance (to the shoreline) in trapped areas versus those sampled by random points indicates that areas close to the shore, particularly those <500 m from the shore, are under-represented in the current trapping protocols, which may influence population estimates if foxes tend to select or avoid areas near the shoreline (Figure C-10).

Trapped areas were also closer to developed areas (Table C-3, Figure C-11), however the mean and median distances differed by less than 150 m, which, again, may have little biological relevance.

The West End of Santa Catalina does not include any paved roads or vegetation chosen as a surrogate for freshwater, therefore trapped and island-wide areas were not compared in relation to these two measures.

Trapped areas and areas sampled by random points differed significantly in terms of vegetation representation, with trapped areas tending to under-represent Barren and Coastal Sage Scrub areas, and tending to over-represent Grassland and Island Chaparral areas (Figure C-12).

Table C-3. Comparison of habitat attributes on Santa Catalina Island's West End (n = 3,799 random points) versus areas trapped with existing protocol on the West End (n = 3,205 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***P***
Slope (degrees)	22.27 (8.82)	21.51 (7.90)	21.66	21.30	-2.52	0.012
Ruggedness Index	0.0112 (0.0131)	0.0102 (0.0114)	0.0065	0.0059	-2.77	0.006
Dist. to Shore (m)	740.83 (492.57)	823.94 (493.11)	660.68	757.20	-7.32	<0.001
Dist. to Paved Roads (m)	---	---	---	---	---	---
Dist. to Developed (m)	1818.80 (1239.6)	1685.42 (1128.3)	1678.39	1540.60	-3.746	<0.001
Dist. to Freshwater (m)	---	---	---	---	---	---

Proposed Scenario A

<u>East End</u>

Assuming a 600-m effective trap radius around each trap, Scenario A samples approximately 28% of Santa Catalina Island's East End (Map 6-5). On the East End of the island, areas trapped with Scenario A had lower slope and ruggedness values than random points on the East End (Table C-4, Figures C-1 and C-2). However, as discussed above in relation to existing protocols, the small absolute differences in slope and ruggedness may not have relevance to fox sampling. Sampled areas were also farther from the shoreline, paved roads, and developed areas, and closer to freshwater, than areas sampled with random points (Table C-4, Figures C-3, C-4, C-5, C-6).

The absolute differences, whether means or medians are considered, were not greater than about 300 m, suggesting that this difference may not have biological relevance. However, visual examination of Figures C-3, C-4, C-5, and C-6, does suggest that some areas may be under-represented. For example, just as in the case of existing protocols, areas close to the shore appear to be under-represented.

Although Scenario A appeared to sample vegetation categories adequately (Figure C-13), a statistical difference was found to exist between trapped areas and areas sampled with random points (Chi-square = 67.95, df = 3, $p < 0.01$). This is apparently due to slight over-sampling of Coastal Sage Scrub and Grassland areas, and under-sampling of Barren and Island Chaparral areas.

Table C-4. Comparison of habitat attributes on Santa Catalina Island's East End (n = 5,000 random points) versus areas trapped in Scenario A on the East End (n = 5,000 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***P***
Slope (degrees)	18.70 (9.00)	16.57 (8.34)	17.69	15.48	-11.83	<0.001
Ruggedness Index	0.0112 (0.0126)	0.0095 (0.0110)	0.0067	0.0056	-6.85	<0.001
Dist. to Shore (m)	1758.63 (1223.9)	2078.94 (1284.4)	1532.94	1835.89	-12.67	<0.001
Dist. to Paved Roads (m)	2914.85 (2255.9)	2988.34 (2144.6)	2336.92	2552.65	-3.15	0.002
Dist. to Developed (m)	1299.38 (878.4)	1513.89 (896.7)	1168.46	1394.59	-12.60	<0.001
Dist. to Freshwater (m)	996.95 (690.2)	874.81 (631.31)	849.32	725.60	-8.74	<0.001

West End

Assuming a 600-m effective trap radius around each trap, Scenario A samples approximately 50% of Santa Catalina Island's West End (Map 6-5). On the West End of the island, areas trapped with Scenario A had lower slope and ruggedness values than areas sampled with random points (Table C-5, Figures C-8 and C-9). However, as discussed above, the small absolute differences in slope and ruggedness may not have relevance to fox sampling. Sampled areas were also farther from the shoreline and closer to developed areas than were random points on the West End (Table C-5, Figures C-10 and C-11). However, the absolute differences, whether means or medians are considered, were less than 300 meters, suggesting that this difference may not have biological relevance. However, visual examination of Figures C-10 and C-11 suggests that some areas may be under-represented. For example, just as in the case of existing protocols, areas close to the shore appear to be under-represented.

On the West End of the island, areas sampled by Scenario A also differed in terms of vegetation composition, as compared to areas sampled with random points (Chi-square = 144.89, df = 3, *p* <0.01). This appears to be due primarily to over-sampling of Grassland and Island Chaparral vegetation and under-sampling of Coast Sage Scrub vegetation (Figure C-14).

Table C-5. Comparison of habitat attributes on Santa Catalina Island's West End (n = 3,799 random points) versus areas trapped in Scenario A on the West End (n = 1,899 random points).

Habitat Measure	Island Mean (sd)	Trapped Area Mean (sd)	Island Median	Trapped Area Median	*Z*	*P*
Slope (degrees)	22.27 (8.82)	19.99 (7.29)	21.66	19.96	-8.68	<0.001
Ruggedness Index	0.0112 (0.0131)	0.0088 (0.0100)	0.0065	0.0049	-7.20	<0.001
Dist. to Shore (m)	740.83 (492.57)	860.74 (501.95)	660.68	842.14	-8.70	<0.001
Dist. to Paved Roads (m)	---	---	---	---	---	---
Dist. to Developed (m)	1818.80 (1239.6)	1640.51 (1168.11)	1678.39	1416.05	-4.80	<0.001
Dist. to Freshwater (m)	---	---	---	---	---	---

Proposed Scenario B

East End

Assuming a 600-m effective trap radius around each trap, Scenario B samples approximately 35% of Santa Catalina Island's East End (Map 6-6). Habitat representation was, in general, slightly better than that found for Scenario A. On the East End of the island, areas trapped with Scenario B had lower slope and ruggedness values than random points on the East End (Table C-6, Figures C-1 and C-2). However, as discussed above, the small absolute differences in slope and ruggedness may not have relevance to fox sampling. Sampled areas were also farther from the shoreline, paved roads, and developed areas, and closer to freshwater (Table C-6, Figures C-3, C-4, C-5, C-6). The absolute differences, whether means or medians are considered, were <400 m, suggesting that this difference may not have biological relevance in relation to island fox movement patterns. However, visual examination of Figures C-3, C-4, C-5, and C-6, does suggest that some areas may be under-represented. For example, just as in the case of existing protocols and Scenario A, areas close to the shore appear to be under-represented.

Although Scenario B appears to sample vegetation categories in proportion to availability on the East End (Figure C-15), a statistical difference was found to exist between trapped areas and areas sampled with random points on the East End (Chi-square = 64.58, df = 3, *p* <0.01). This is apparently due to slight over-sampling of Coastal Sage Scrub and Grassland areas, and under-sampling of Barren and Island Chaparral areas.

West End

Scenarios A and B are identical in relation to areas trapped on Santa Catalina Island's West End, because the number of trapping units and their locations are identical in the two scenarios in this part of the island. For this reason, results of habitat representation for Scenario B on the West End are identical to those for Scenario A shown above.

Table C-6. Comparison of habitat attributes on Santa Catalina Island's East End (n = 5,000 random points) versus areas trapped in Scenario B on the East End (n = 5,000 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***P***
Slope (degrees)	18.7 (9.00)	16.44 (8.08)	17.7	15.5	-12.18	<0.001
Ruggedness Index	0.0112 (0.013)	0.0093 (0.0113)	0.0067	0.0051	-9.42	<0.001
Dist. to Shore (m)	1758.6 (1223.9)	2026.2 (1206.8)	1532.9	1811.7	-11.83	<0.001
Dist. to Paved Roads (m)	2914.9 (2255.9)	3180.6 (2153.2)	2336.92	2695.8	-7.81	<0.001
Dist. to Developed (m)	1299.34 (878.4)	1416.7 (847.9)	1168.5	1282.1	-7.77	<0.001
Dist. to Freshwater (m)	996.95 (690.2)	822.4 (616.9)	849.3	679.5	-13.04	<0.001

Conclusions

Since 2000, Santa Catalina has been trapped with an extensive array of transects, including a total of 605 traps. This trapping effort samples approximately 79% and 84% of the East and West ends, respectively, if a 600-m effective trap radius is assumed. In general, existing protocols sample habitat variability on the island more effectively than Scenario A and B, no doubt due to the larger proportion of the island sampled. Scenarios A and B only sample 28% and 35% of the East End, respectively, while each samples 50% of the West End. Trapping Scenario B tended to sample the island more adequately than Scenario A. Statistically, areas sampled by all three trapping scenarios (including existing protocols) differ from random points on the island for all habitat measures examined, with the exception of distance to paved roads and developed areas on the East End of the island under existing trap protocols. However, as discussed above, statistical differences may not indicate biologically relevant differences. For example, statistical differences were found in slope and ruggedness but absolute differences were small and may not influence trapping results. In some cases, however, under-sampling of some areas, such as areas close to the shore, may bias trapping results if fox density is different close to the shore than in other areas. Increasing sampling in some areas, such as close to the shore, will remain problematic, however, due to logistic and safety issues, and this will likely mean that any logistically feasible protocol will also sample areas that area less steep and less rugged than island-wide areas. We suggest that future research focused on fox habitat use and selection should be conducted to test whether under- or over-sampling certain habitat characteristics is expected to bias trapping results.

Literature Cited

Fowler, J., L. Cohen, and P. Jarvis. 1998. Practical Statistics for Field Biology. 2nd ed. John Wiley and Sons, New York, NY. 259pp.

Sokal, R.R., and F.J. Rohlf. 1995. Biometry: The Principles and Practices of Statistics in Biological Research. 3rd ed.. W.H. Freeman and Company, New York, NY. 887pp.

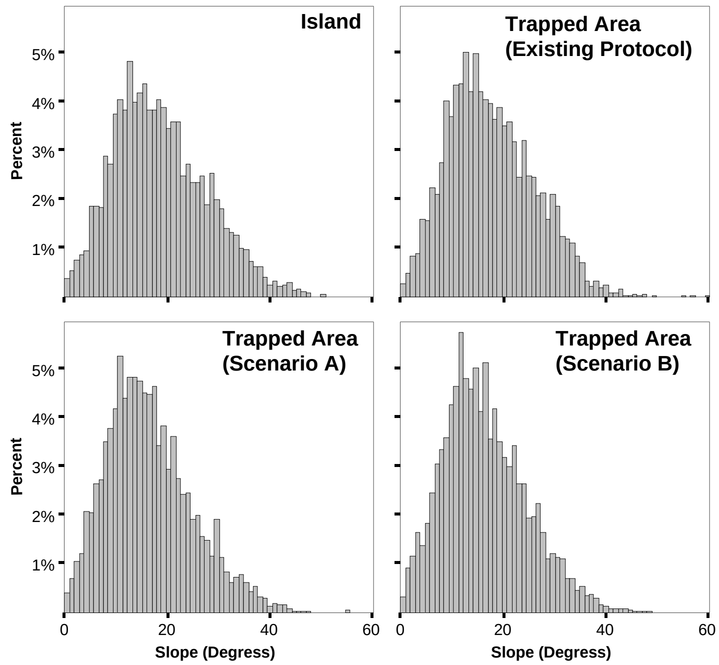

Figure C-1. Distribution of slope (as percent of total random points) on Santa Catalina Island's East End versus in areas trapped with three trapping scenarios on the East End (Existing Protocol, Scenario A, and Scenario B).

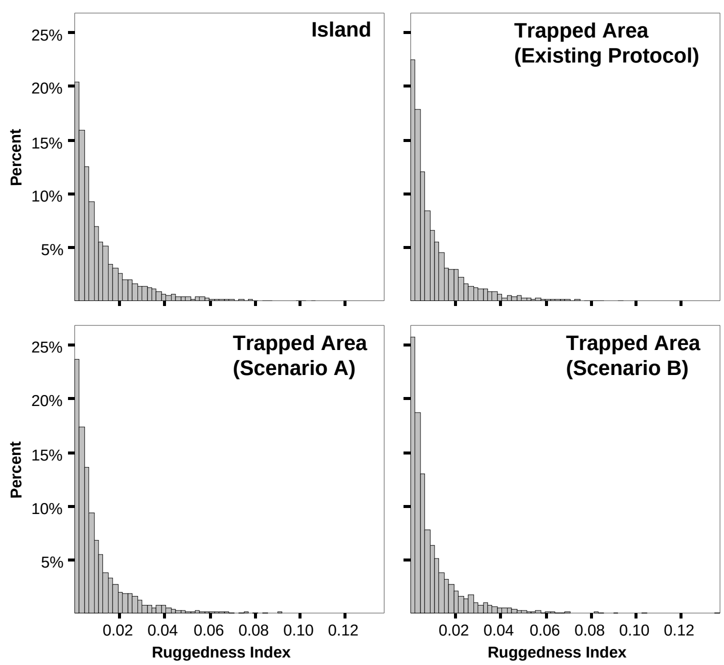

Figure C-2. Distribution of ruggedness index (as percent of total random points) on Santa Catalina Island's East End versus areas trapped with three trapping scenarios on the East End (Existing Protocol, Scenario A, Scenario B).

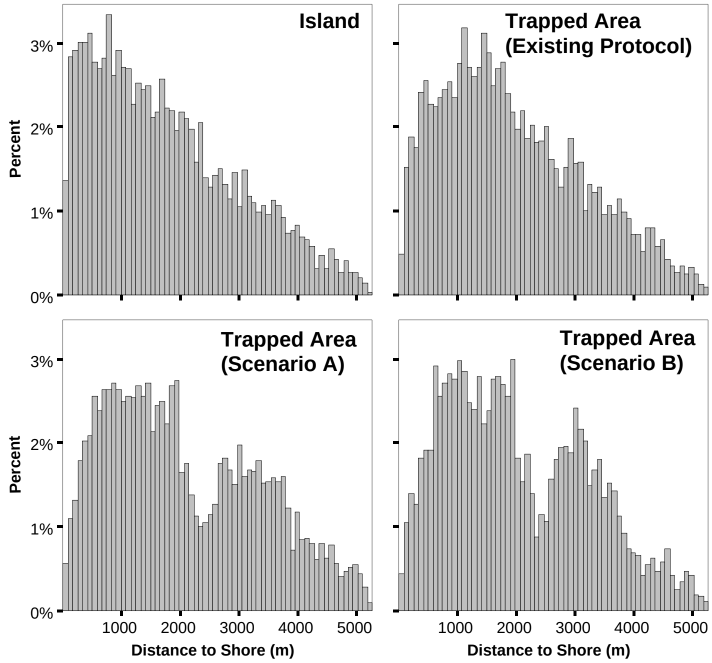

Figure C-3. Distribution of distance to the shoreline (as % of total random points) on Santa Catalina Island's East End versus areas trapped with three trapping scenarios on the East End (Existing Protocol, Scenario A, Scenario B).

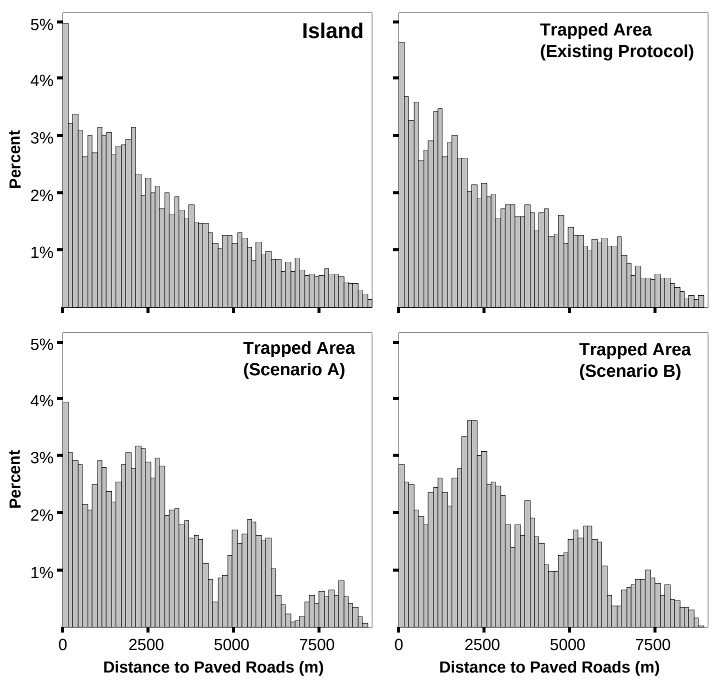

Figure C-4. Distribution of distance to paved roads (as % of total random points) on Santa Catalina Island's East End versus areas trapped with three trapping scenarios on the East End (Existing Protocol, Scenario A, Scenario B).

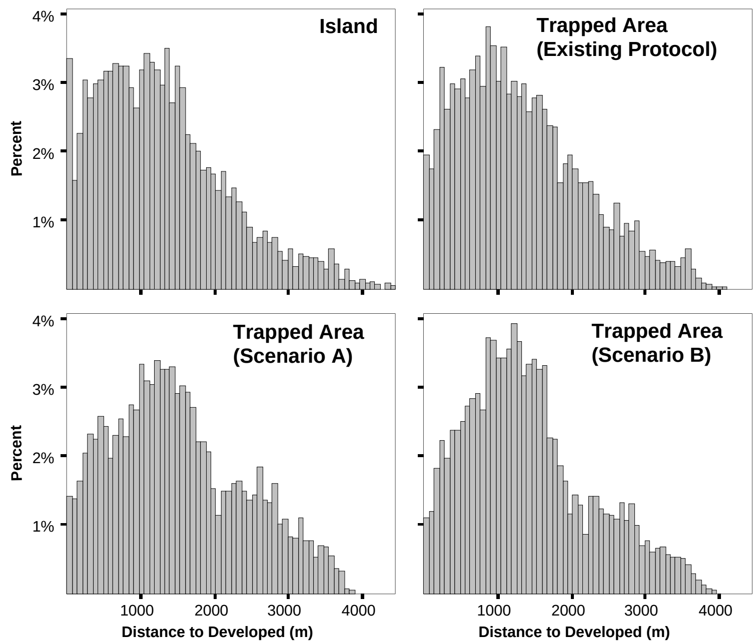

Figure C-5. Distribution of distance to developed areas (as % of total random points) on Santa Catalina Island's East End vs areas trapped with three trapping scenarios on the East End (Existing Protocol, Scenario A, Scenario B).

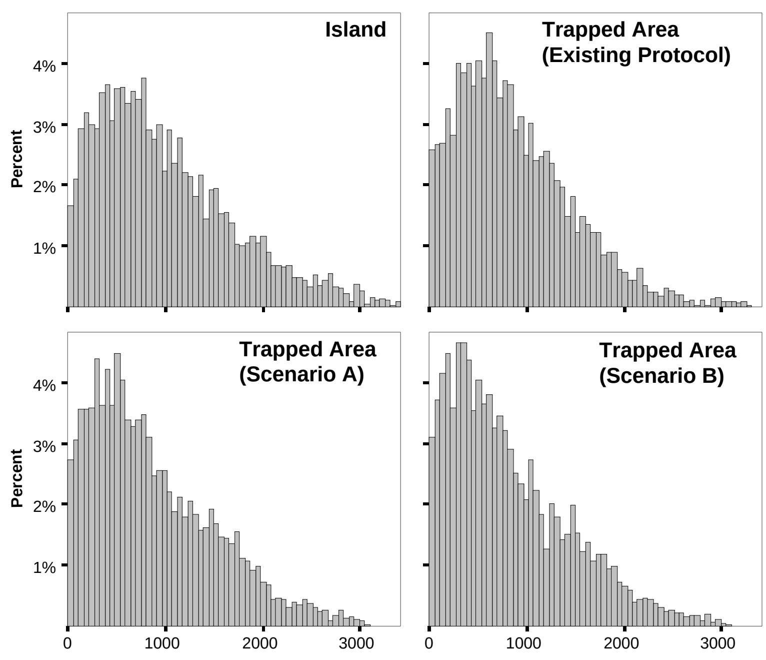

Figure C-6. Distribution of distance to freshwater (as percent of total random points) on Santa Catalina Island's East End versus areas trapped with three trapping scenarios (Existing Protocol, Scenario A, and Scenario B).

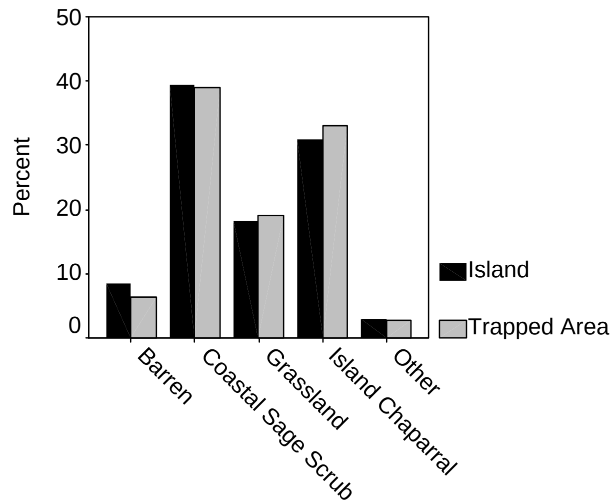

Figure C-7. Distribution of vegetation types (as percent of total random points) on Santa Catalina Island's East End versus areas trapped with Existing Protocol on the East End.

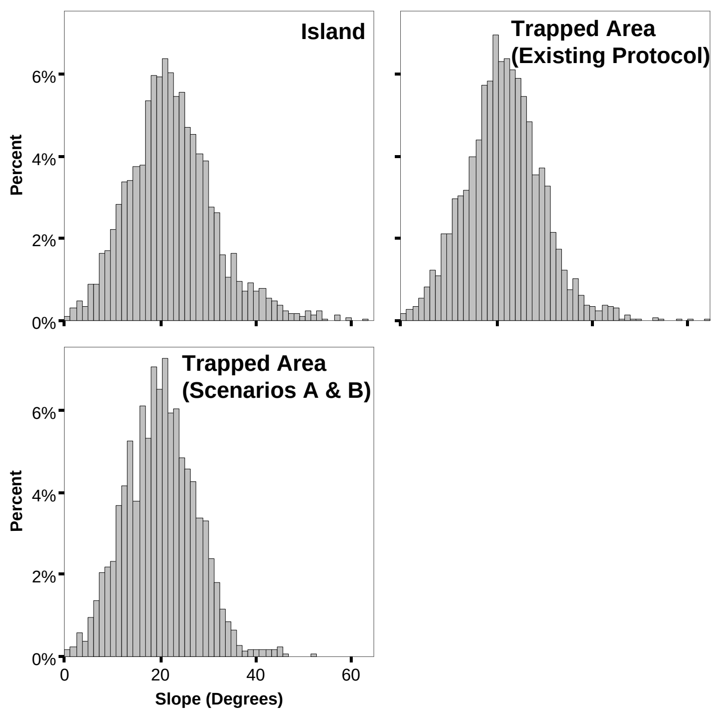

Figure C-8. Distribution of slope (as percent of total random points) on Santa Catalina Island's West End versus in areas trapped with three trapping scenarios on the West End (Existing Protocol, Scenario A, and Scenario B).

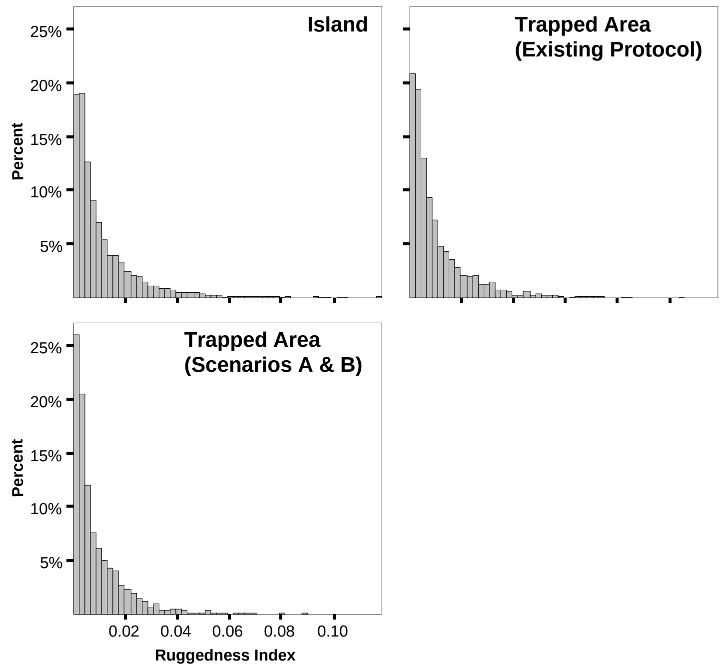

Figure C-9. Distribution of ruggedness index (as % of total random points) on Santa Catalina Island's West End versus areas trapped with three trapping scenarios on the West End (Existing Protocol, Scenario A, and Scenario B).

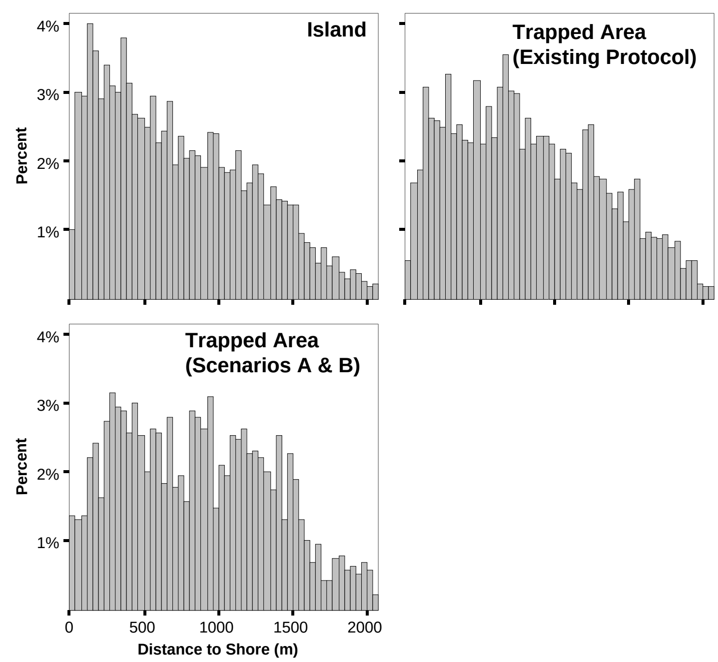

Figure C-10. Distribution of distance to shoreline (as % of total random points) on Santa Catalina Island's West End vs areas trapped with three trapping scenarios on the West End (Existing Protocol, Scenario A, and Scenario B).

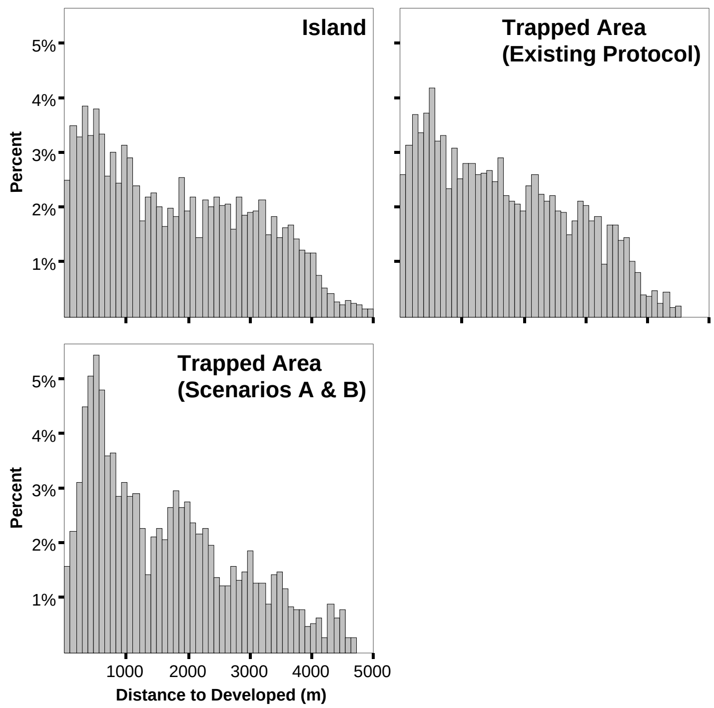

Figure C-11. Distribution of distance to developed areas (as percent of total random points) on Santa Catalina Island's West End vs areas trapped with three trapping scenarios on the West End (Existing Protocol, Scenario A, and Scenario B).

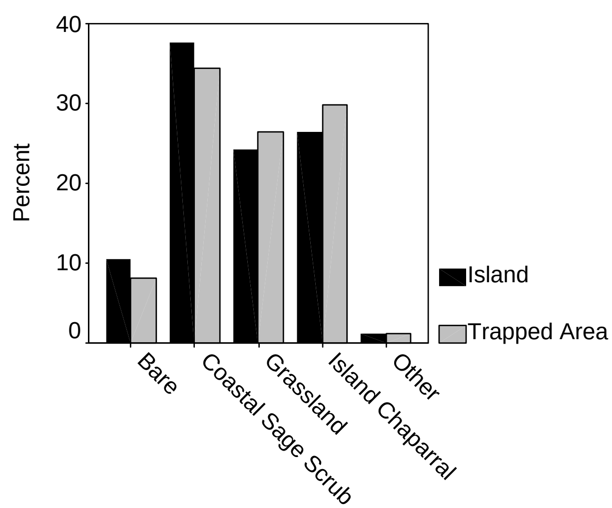

Figure C-12. Distribution of vegetation types (as percent of total random points) on Santa Catalina Island's West End versus areas trapped with Existing Protocol on the West End.

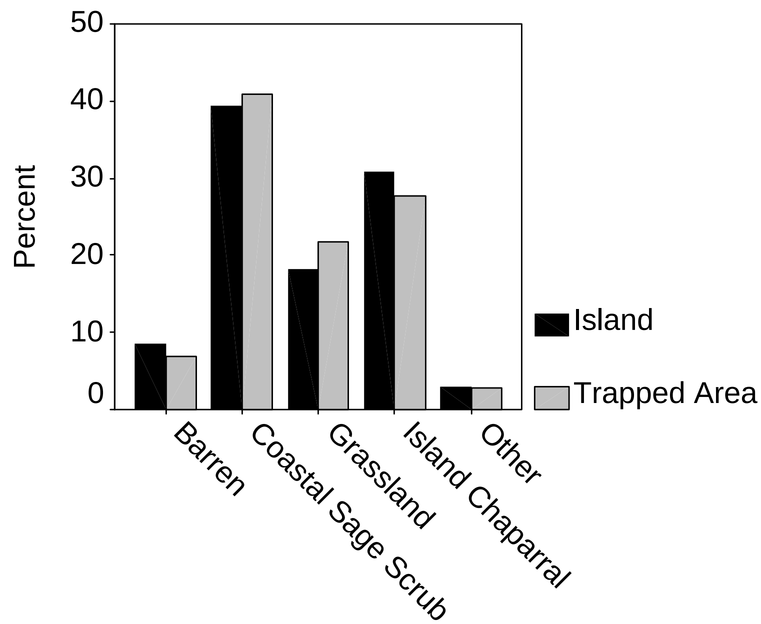

Figure C-13. Distribution of vegetation types (as percent of total random points) on Santa Catalina Island's East End versus areas trapped with Scenario A on the East End.

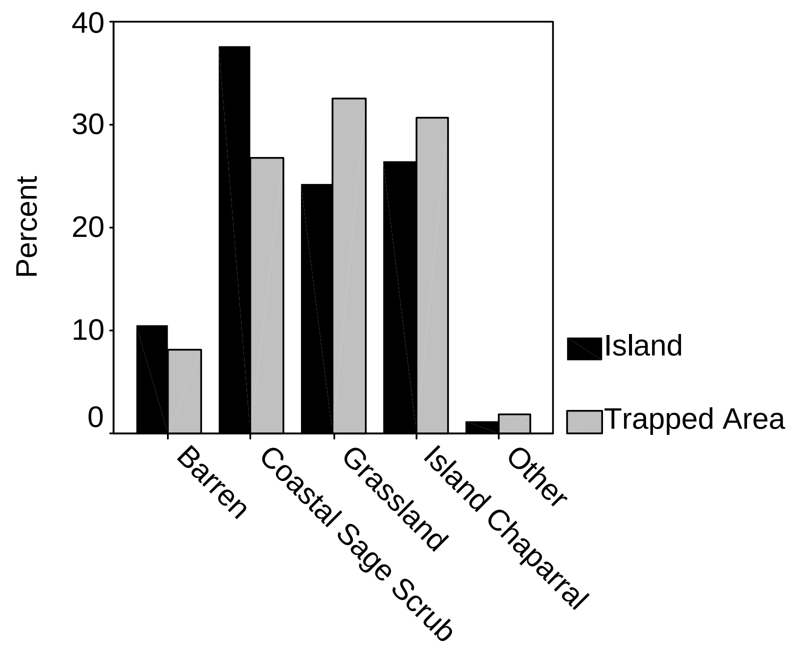

Figure C-14. Distribution of vegetation types (as percent of total random points) on Santa Catalina Island's West End versus areas trapped with Scenarios A/B on the West End.

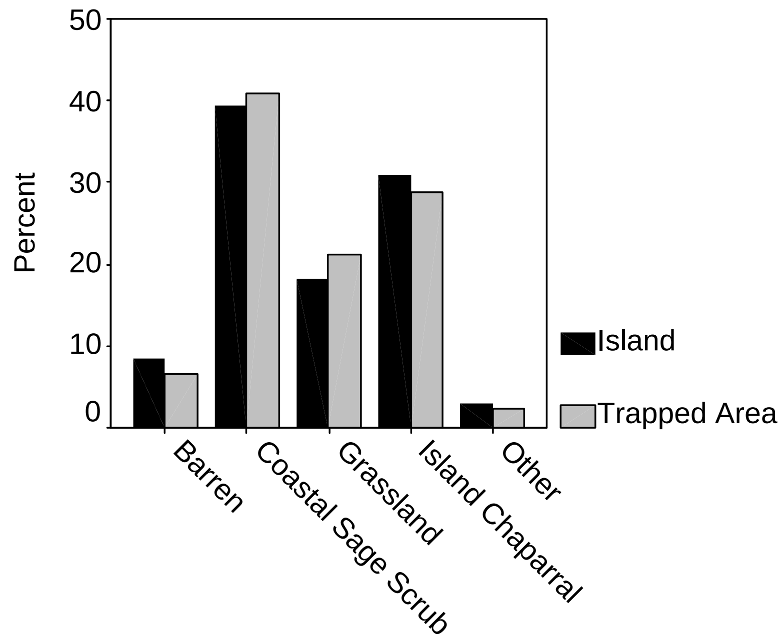

Figure C-15. Distribution of vegetation types (as percent of total random points) on Santa Catalina Island's East End versus areas trapped with Scenario B on the East End.

Appendix D

Univariate Representation Analysis of Proposed Trapping Scenarios on Santa Rosa Island

Introduction

This representation analysis examines how well recommended trapping protocols represent habitat variation on Santa Rosa Island. Because no standardized trapping protocol has been established for this island, we did not evaluate an existing protocol as we did on other islands. The goal of evaluating proposed trapping scenarios was to provide managers with additional information on which to base decisions about trapping protocols. In addition, increased knowledge regarding habitat representation of each trapping scenario may help identify research needs relative to habitat use and selection.

Methods

We identified habitat variables currently available as GIS coverages or that could be created from existing GIS coverages, and for which we have empirical evidence or biological rationale to suspect that they may influence island fox habitat quality or population dynamics. Although we can not know or measure all habitat characteristics important to island foxes, we strived to maximize representation of the following habitat attributes that we can measure: vegetation type, slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources. It is likely that other habitat characteristics also influence fox populations, but some of these will correlate highly with the variables we selected (e.g., distance to canyon bottoms would correlate strongly with our ruggedness index), and others are not currently available to measure (e.g., cat densities or prey densities). This analysis should be viewed as preliminary, and we strongly recommend that future data from radio-collared foxes be used to evaluate and identify habitat features that influence fox densities or habitat selection.

We created data layers for each of the continuous variables (slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources) in the following manner:

- Slope. We derived a slope layer from the USGS 30-m DEM. We chose to create a slope layer in degrees.
- Ruggedness. We created a Ruggedness raster layer using an Avenue script created and provided by Mark Sappington (National Park Service) and Kathy Longshore (U.S. Geological Survey). This measure provides an index of ruggedness which ranges from 0 to 1, with 0 representing completely flat terrain and 1 representing the most rugged terrain. We used the USGS 30-m DEM as the basis for the algorithm, after converting its elevation values from feet to meters, and used a 90x90-m moving window to calculate ruggedness.

- Distance to shoreline. We created a raster layer of the distance-to-shoreline using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to roads. We created a raster layer of the distance to roads using the Distance ->Straight Line tool provided in the Spatial Analyst extension. The road data layer was provided by NPS.
- Distance to developed. We created a raster layer of the distance to developed areas using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to freshwater. Because a map of freshwater sources on Santa Rosa Island is not currently available, we used the USGS hydrology layer as a surrogate. This layer represents drainages and ravines, which may be more likely to contain surface freshwater or runoff than other areas, but are not guaranteed to provide water.
- Vegetation. We used a vegetation layer created and provided by the National Park Service. We examined the composition of vegetation across the entire island, and attempted to reduce the number of vegetation classifications to represent major vegetation types. The original and newly created classifications are shown in Table D-1.

Table D-1. Vegetation classifications on Rosa Island, as originally classified and as grouped for analysis.

Original Classification	Representation of Original Classification on Island (%)	Vegetation as Categorized for Analysis
Grassland	69.99	Grassland
Coastal Sage Scrub	16.92	Coastal Sage Scrub
Bare	6.17	Bare
Chaparral	4.70	Chaparral
Lupine Scrub	0.91	Lupine/Caliche/Baccharis Scrub
Coastal Bluff	0.44	Other
Agricultural Area	0.24	Other
Caliche Scrub	0.22	Lupine/Caliche/Baccharis Scrub
Marsh	0.18	Other
Coastal Strand	0.11	Other
Mixed Woodland	0.11	Other
Torrey Pine	0.11	Other
Island Oak	0.07	Other
Unknown	0.05	Other
Baccharis Scrub	0.03	Lupine/Caliche/Baccharis Scrub
Pond	0.03	Other
Closed-cone Pine	0.01	Other
Eucalyptus	0.01	Other
Southern Riparian Woodland	0.01	Other
NPS Trailer	0.00	Other

Habitat characteristics were determined from two separate sets of random points; one distributed over the entire island and one distributed on trapped areas only. Trapped areas were defined as all locations within a 600-m buffer of a trap, excluding open water and avoiding double-counting of overlap areas for grids or traps <1,200 m apart. The 600-m buffer distance, added to represent the effective trap area of each trap, is equal to the mean of the mean maximum distances moved for each trapping session for all years for grids on San Clemente, San Miguel, San Nicolas, and Santa Cruz islands (V. Bakker, pers. comm.). The number of random points was chosen by first placing points along a systematic grid with 90-m spacing, to result in a density of 144 points/km^2, and then applying this density of points randomly to the island and the trapped area. For our analysis, we randomly chose 5,000 points from the island and from the trapped points.

We used the Mann-Whitney test (Sokal and Rohlf 1995) to test whether continuous variables (slope, ruggedness, distance to roads, etc.) differed between the island and trapped areas. To compare the composition of vegetation types, we used a chi-square goodness of fit test (Fowler et al. 1998), to compare vegetation composition of the trapped area versus on the entire island. We also visually compared the distributions of habitat attributes on the island versus those on trapped areas.

Results and Discussion

Scenario A

Assuming a 600-m effective trap radius around each trap, Scenario A samples approximately 30% of Santa Rosa Island (Map 7-5). This proposed trapping scenario differed from island-wide areas in all continuous habitat measures except for distance to developed areas (Table D-2). Sampled areas had lower slope and ruggedness than island-wide areas (Figures D-1 and D-2); however, the absolute differences were small and may not have biological significance. For example, the difference in mean and median slopes was <3°, while the differences in mean and median ruggedness indices were extremely small compared to the range of the ruggedness index, which has a value of 0 for completely flat terrain and a value of 1 for extremely rugged terrain.

Areas sampled by Scenario A were closer to the shore and to roads, and farther from freshwater (Table D-2, Figures D-3, D-4, and D-6). However, again, it is not known if these statistical differences would represent biological differences, because absolute differences between island-wide and trapped areas are relatively small compared to movement patterns observed in island foxes. For each of these measures, mean and median values of trapped areas differed from those of island-wide areas by <500 m.

Scenario A sampled all the vegetation categories included in this analysis, and visually appeared to represent the vegetation categories quite well (Figure D-7). However, a significant difference existed in the distribution of trapped areas versus island-wide areas (Chi-square = 61.28, df = 4, p <0.01), due to under-sampling of coastal sage scrub and slight over-sampling of the remaining categories.

Scenario B

Assuming a 600-m effective trap radius around each trap, Scenario B samples approximately 23% of Santa Rosa Island (Map 7-6). Areas sampled with this trapping scenario differed from island-wide areas in all continuous measures, with the exception of distance to roads (Table D-3). However, as discussed in relation to Scenario A above, it is not know if these statistical differences represent biological differences. Some habitat measures differed more with this scenario than with Scenario A. For example, median differences between island-wide and trapped areas differed by >700 m in distance to develop areas, and this could influence trap data if foxes avoid or select habitat near developed areas.

Scenario B sampled all vegetation categories included in this analysis, but didn't sample them in proportion to availability (Chi-square = 134.59, df = 4, p <0.01). This difference is due to under-sampling bare, chaparral, and coastal sage scrub areas, and over-sampling grassland and lupine/caliche/baccharis scrub areas (Figure D-8).

Table D-2. Comparison of habitat attributes on Santa Rosa Island (n = 5,000 random points) versus areas trapped with proposed trapping Scenario A (n = 5,000 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	13.71 (8.21)	11.79 (7.89)	13.17	10.66	-11.78	<0.001
Ruggedness Index	0.0072 (0.0092)	0.0053 (0.0075)	0.0039	0.0024	-13.09	<0.001
Dist. to Shore (m)	2103.25 (1548.4)	1748.93 (1349.16)	1758.01	1306.98	-10.63	<0.001
Dist. to Roads (m)	1348.04 (1226.3)	1368.24 (1371.71)	997.25	831.93	-3.94	<0.001
Dist. to Developed (m)	5002.55 (3169.1)	5187.02 (3490.35)	4455.74	4967.67	-1.36	0.174
Dist. to Freshwater (m)	417.36 (438.66)	466.67 (497.34)	300.00	330.00	-4.53	<0.001

Conclusions

Areas sampled by Scenarios A and B differ statistically from island wide-wide areas in all continuous habitat measures, with the exception of distance to developed areas, which does not differ between the island and Scenario A, and distance to roads, which doesn't differ between the island and Scenario B. It is possible, however, that these statistical differences may not indicate biological differences because, in most cases, absolute differences are quite small in relation to the scale of measurement (e.g., slope and ruggedness) or in comparison to fox movement distances (e.g., distance to the shore, distance to freshwater). For example, distance to freshwater is significantly different but medians and means of island-wide versus trapped areas differed by <50 m, which may not have relevance to fox habitat selection. 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 the may provide valuable resources such as denning sites or foraging areas. It is unknown if a difference of 50 m has relevance to selection or avoidance of ravines and drainages.

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. Although Scenario B tends to resembled the island most closely in terms of slope, distance to roads and freshwater, and possibly ruggedness, Scenario A samples the island more adequately in terms of distance to the shore and develop areas, and in vegetation composition.

It is not surprising that trapped areas had lower slope and ruggedness than island-wide areas, since our placement of trapping units specifically avoided high slopes (those ≥30%, or 16.7°), for logistic and safety reasons. It is likely that any feasible trapping protocol for Santa Rosa Island would differ from island-wide areas in these two measures.

Table D-3. Comparison of habitat attributes on Santa Rosa Island (n = 5,000 random points) versus areas trapped with proposed trapping Scenario B (n = 5,000 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	13.71 (8.21)	12.38 (7.81)	13.17	11.69	-7.82	<0.001
Ruggedness Index	0.0072 (0.0092)	0.0055 (0.0076)	0.0039	0.0026	-11.04	<0.001
Dist. to Shore (m)	2103.25 (1548.4)	1684.78 (1350.59)	1758.01	1261.43	-13.06	<0.001
Dist. to Roads (m)	1348.04 (1226.3)	1348.95 (1164.96)	997.25	933.38	-0.956	0.339
Dist. to Developed (m)	5002.55 (3169.1)	5270.82 (3113.77)	4455.74	5161.61	-5.65	<0.001
Dist. to Freshwater (m)	417.36 (438.66)	445.21 (485.89)	300.00	318.90	-2.51	0.012

Literature Cited

Fowler, J., L. Cohen, and P. Jarvis. 1998. Practical Statistics for Field Biology. 2nd ed. John Wiley and Sons, New York, NY. 259pp.

Sokal, R.R., and F.J. Rohlf. 1995. Biometry: The Principles and Practices of Statistics in Biological Research. 3rd ed.. W.H. Freeman and Company, New York, NY. 887pp.

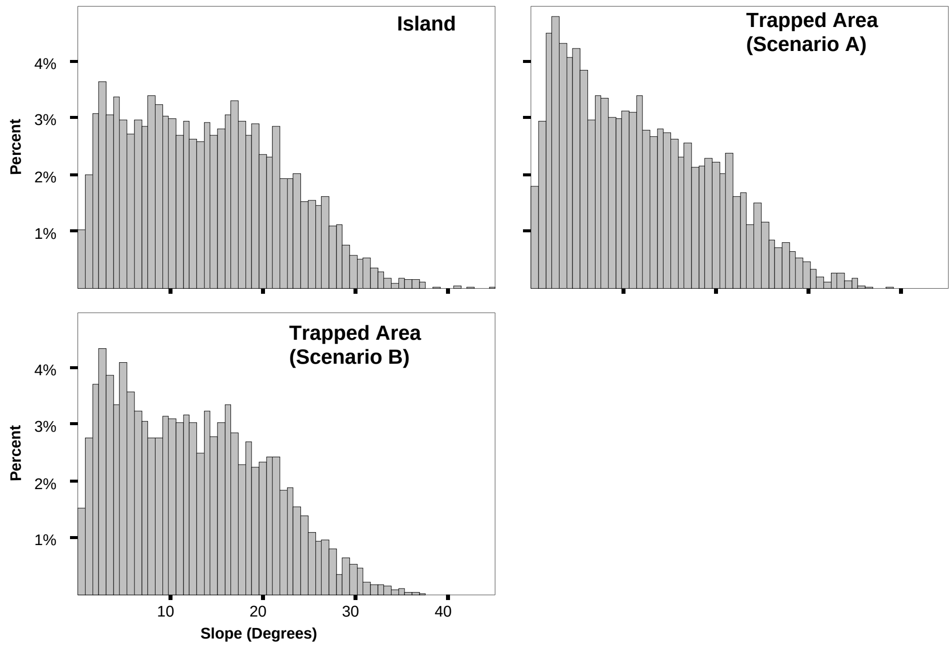

Figure D-1. Distribution of slope (as percent of random points) on Santa Rosa Island versus in areas trapped with proposed trapping Scenarios A and B.

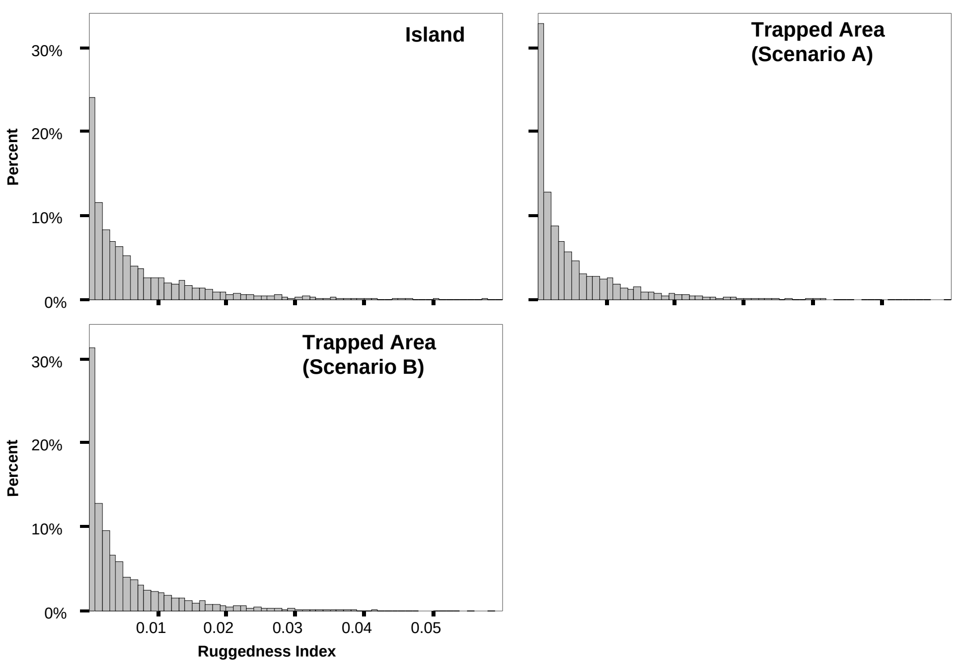

Figure D-2. Distribution of ruggedness (as percent of random points) on Santa Rosa Island versus in areas trapped with proposed trapping Scenarios A and B.

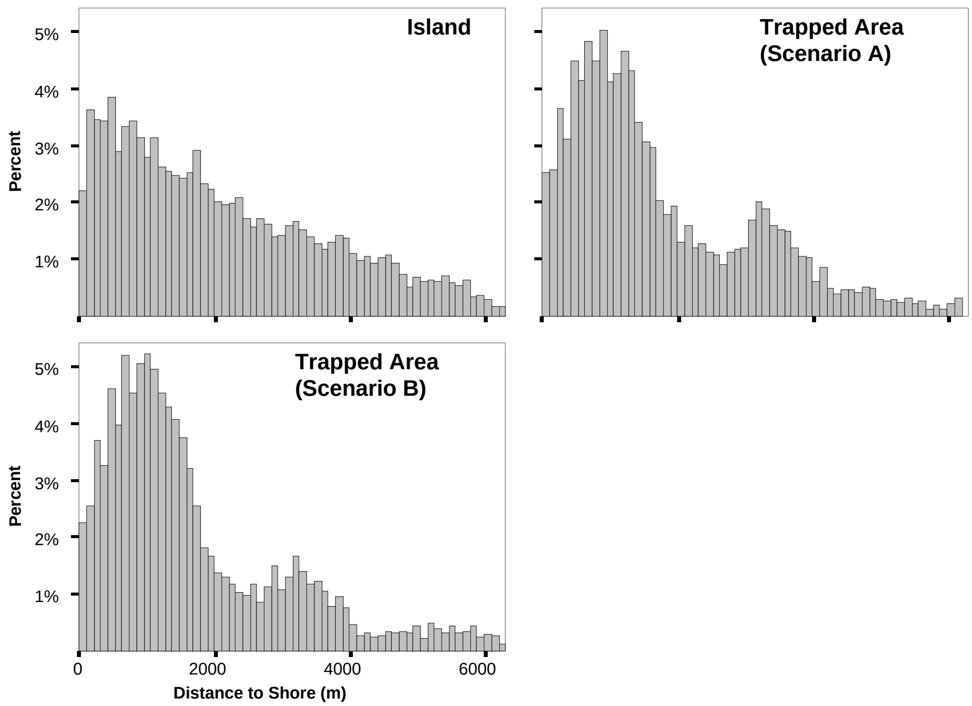

Figure D-3. Distribution of distance to shore (as percent of random points) on Santa Rosa Island versus in areas trapped with proposed trapping Scenarios A and B.

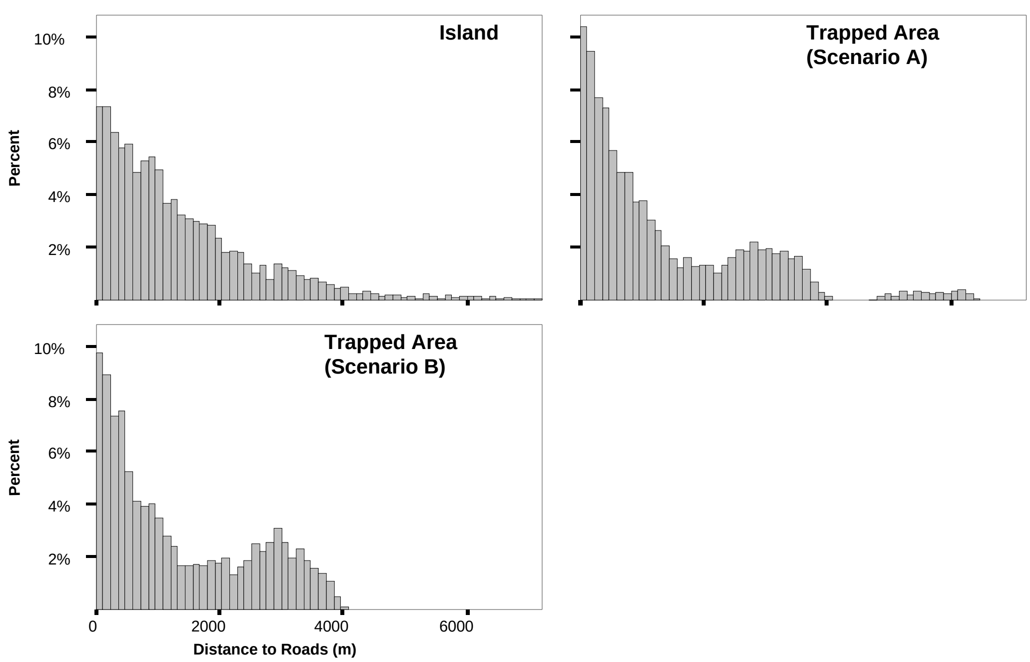

Figure D-4. Distribution of distance to roads (as percent of random points) on Santa Rosa Island versus in areas trapped with proposed trapping Scenarios A and B.

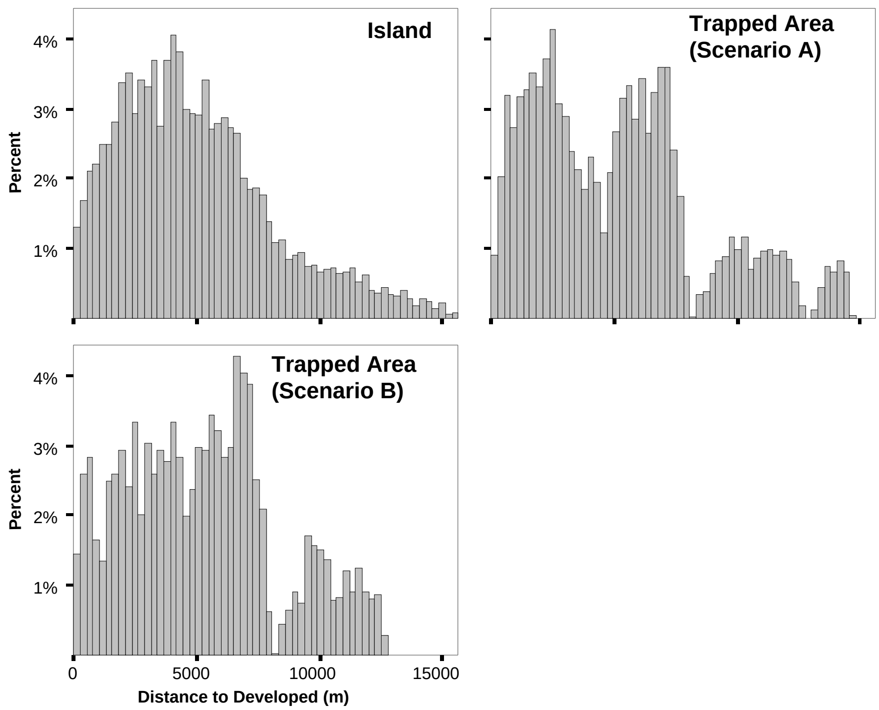

Figure D-5. Distribution of distance to developed areas (as percent of random points) on Santa Rosa Island versus in areas trapped with proposed trapping Scenarios A and B.

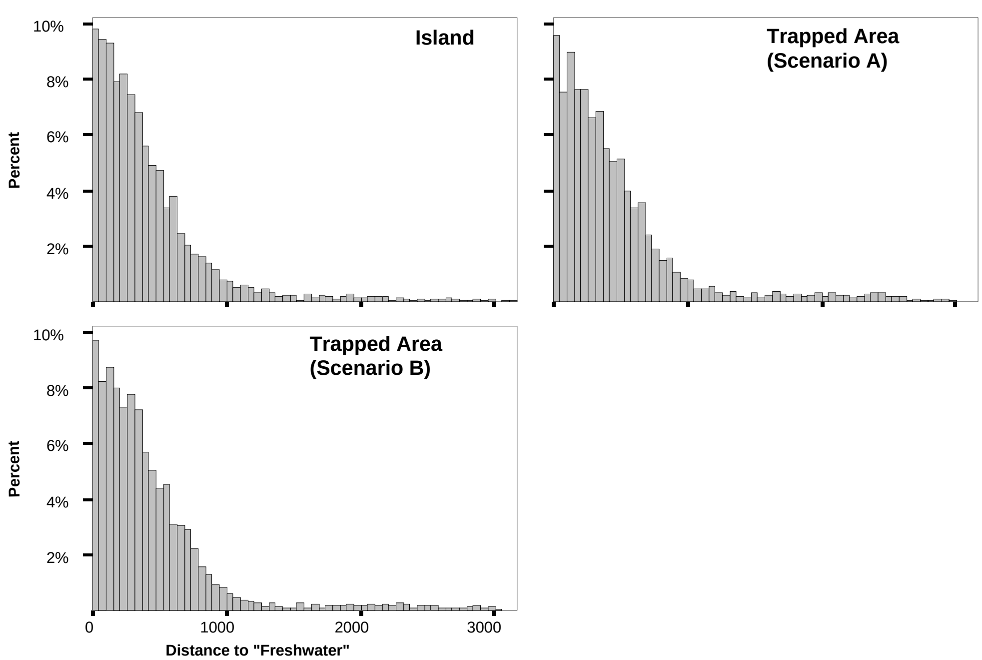

Figure D-6. Distribution of freshwater (as percent of random points) on Santa Rosa Island versus in areas trapped with proposed trapping Scenarios A and B.

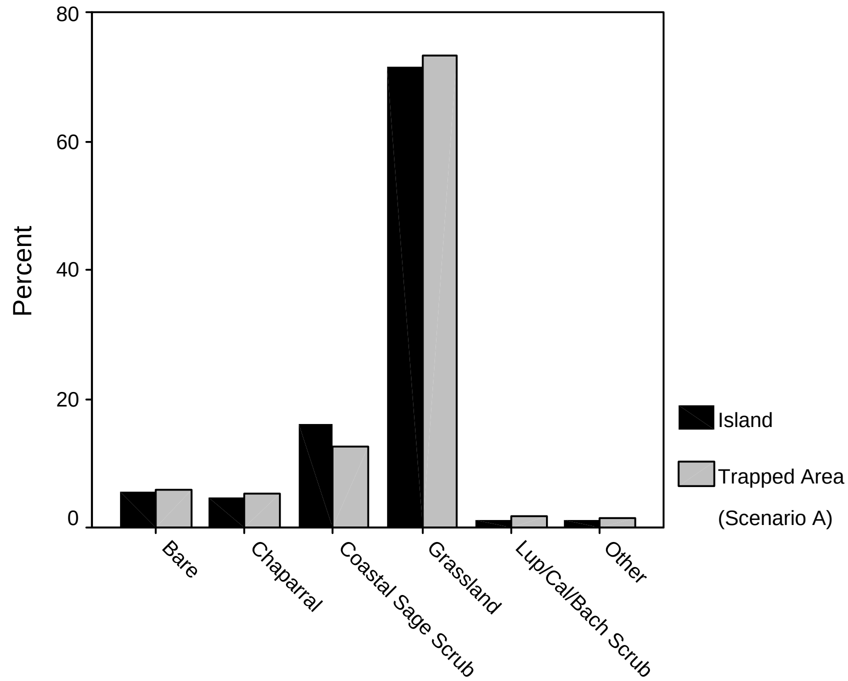

Figure D-7. Distribution of vegetation types (as percent of random points) on Santa Rosa Island versus in areas trapped with Scenario A.

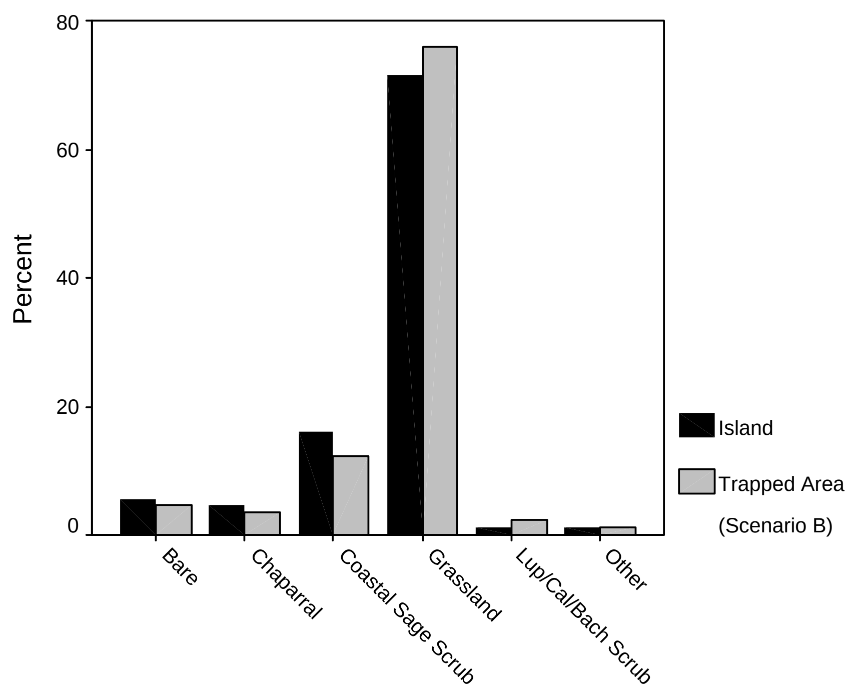

Figure D-8. Distribution of vegetation types (as percent of random points) on Santa Rosa Island versus in areas trapped with Scenario B.

Appendix E

Univariate Representation Analysis of Existing and Proposed Trapping Scenarios on Santa Cruz Island

Introduction

This representation analysis examines how well existing and recommended trapping protocols represent habitat variation on Santa Cruz Island. The goal of evaluating the existing protocol was to identify gaps in island representation that could be addressed in proposed trapping scenarios, and to provide a baseline comparison with which to evaluate proposed scenarios. This information is intended to provide managers with additional information on which to base decisions about trapping protocols. In addition, increased knowledge regarding habitat representation of each trapping scenario may help identify research needs relative to habitat use and selection.

Methods

We identified habitat variables currently available as GIS coverages or that could be created from existing GIS coverages, and for which we have empirical evidence or biological rationale to suspect that they may influence island fox habitat quality or population dynamics. Although we can not know or measure all habitat characteristics important to island foxes, we strived to maximize representation of the following habitat attributes that we can measure: vegetation type, slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources. It is likely that other habitat characteristics also influence fox populations, but some of these will correlate highly with the variables we selected (e.g., distance to canyon bottoms would correlate strongly with our ruggedness index), and others are not currently available to measure (e.g., prey densities). This analysis should be viewed as preliminary, and we strongly recommend that future data from radiocollared foxes be used to evaluate and identify habitat features that influence fox densities or habitat selection.

We created data layers for each of the continuous variables (slope, terrain ruggedness, distance to paved roads, distance to shoreline, distance to developed areas, and distance to freshwater sources) in the following manner:

- Slope. We derived a slope layer from the USGS 30-m DEM. We chose to create a slope layer in degrees.
- Ruggedness. We created a Ruggedness raster layer using an Avenue script created and provided by Mark Sappington (National Park Service) and Kathy Longshore (U.S. Geological Survey). This measure provides an index of ruggedness which ranges from 0 to 1, with 0 representing completely flat terrain and 1 representing the most rugged terrain. We used the USGS 30-m DEM as the basis for the algorithm, after converting its

elevation values from feet to meters, and used a 90x90-m moving window to calculate ruggedness.

- Distance to shoreline. We created a raster layer of the distance-to-shoreline using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to roads. We created a raster layer of the distance to roads using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Distance to developed. We created a raster layer of the distance to developed areas using the Distance ->Straight Line tool provided in the Spatial Analyst extension.
- Vegetation. We used a vegetation layer created and provided by The Nature Conservancy. We examined the composition of vegetation across the entire island, and attempted to reduce the number of vegetation classifications to represent major vegetation types. The original and newly created classifications are shown in Table E-1.

Although we evaluated the distance of trapped areas to sources of freshwater for the other four islands, we opted to exclude this measure from the Santa Cruz Island analysis. This decision was based on the fact that a large number of un-mapped springs and seeps occurred on the island. For other islands, in the absence of actual water data, we used selected vegetation associations as surrogates for freshwater. However, the vegetation map for Santa Cruz, which also included locations of seeps and springs, was known to greatly underestimate the number of water sources on the island. Given that this would include a large known error into the analysis we excluded this measure.

Habitat characteristics were determined from two separate sets of random points; one distributed over the entire island and one distributed on trapped areas only. Trapped areas were defined as all locations within a 600-m buffer of a trap, excluding open water and avoiding double-counting of overlap areas for grids or traps <1,200 m apart. The 600-m buffer distance, added to represent the effective trap area of each trap, is equal to 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, pers. comm.). The number of random points was chosen by first placing points along a systematic grid with 90-m spacing, to result in a density of 144 points/km^2, and then applying this density of points randomly to the island and the trapped area. For our analysis, we randomly chose 5,000 points from the island and from the trapped points.

We used the Mann-Whitney test (Sokal and Rohlf 1995) to test whether continuous variables (slope, ruggedness, distance to roads, etc.) differed between the island and trapped areas. To compare the composition of vegetation types, we used a chi-square goodness of fit test (Fowler et al. 1998), to compare vegetation composition of the trapped area versus on the entire island. We also visually compared the distributions of habitat attributes on the island versus those on trapped areas.

Table E-1. Vegetation classifications on Santa Cruz Island, as originally classified and as grouped for analyses.

Original Classification	Vegetation as Categorized for Analysis
Forests and Woodlands	
Temperate Broadleaf Sclerophyll Evergreen Forest	Forests/Woodlands-non-conifer
Ironwood Alliance	Forests/Woodlands-non-conifer
Eucalyptus Stands	Forests/Woodlands-non-conifer
Island Cherry-(Island Scrub Oak-Toyon)	Forests/Woodlands-non-conifer
Temperate Needleleaf Evergreen Forests	Forests/Woodlands-conifer
Introduced Pines or Cypress	Forests/Woodlands-conifer
Bishop Pine Alliance	Forests/Woodlands-conifer
Temporarily Flooded Cold Season Deciduous Forests	Forests/Woodlands-non-conifer
Big Leaf Maple Alliance	Forests/Woodlands-non-conifer
Fremont Cottonwood-Black Cottonwood Superalliance	Forests/Woodlands-non-conifer
Cold Season Deciduous Forests	Forests/Woodlands-non-conifer
Xeric Sclerophyll Evergreen Woodlands	Forests/Woodlands-non-conifer
Coast Live Oak Alliance	Forests/Woodlands-non-conifer
Canyon Live Oak Alliance	Forests/Woodlands-non-conifer
Cold Season Deciduous Woodlands	
Shrublands	
Temperate Broadleaf Sclerophyll Evergreen Shrublands	Evergreen Shrublands
McMinn's Manzanita	Evergreen Shrublands
Chamise Alliance	Evergreen Shrublands
Island Scrub Oak Alliance	Evergreen Shrublands
Island Manzanita Alliance	Evergreen Shrublands
Birch-leaf Mountain Mahogany Alliance	Evergreen Shrublands
Lemonadeberry Alliance	Evergreen Shrublands
Temperate Microphyllous Evergreen Shrublands	Evergreen Shrublands
Coyote Brush Alliance	Evergreen Shrublands
Mulefat Alliance	Evergreen Shrublands
Temperate Xeric Mixed Drought-Deciduous Shrublands	Deciduous Shrublands
Coastal Bluff Scrub Habitat	Deciduous Shrublands
Australian Saltbush	Deciduous Shrublands
Inland Bluff Scrub Habitat	Deciduous Shrublands
California Sagebrush Alliance	Deciduous Shrublands
Santa Cruz Island Buckwheat Alliance	Deciduous Shrublands
Saint Catherine's Lace Alliance	Deciduous Shrublands
Island Bush Monkeyflower-Island Bristleweed-Paintbrush	Deciduous Shrublands
Temporarily Flooded Cold Season Deciduous Shrublands	Deciduous Shrublands
Mixed Arroyo Willow-Mule Fat	Deciduous Shrublands
Arroyo Willow Alliance	Deciduous Shrublands
Herbaceous	
Saturated Temperate Perennial Graminoids	Herbaceous-non-fennel
Bulrush-Cattail	Herbaceous-non-fennel
Seasonally or Temporarily Flooded Graminoids	Herbaceous-non-fennel
Seasonally/Temp. Flooded Sprs., Seeps, Vernal Pools	Herbaceous-non-fennel
Tall Temperate Annual Graminoids	Herbaceous-non-fennel
Fennel	Herbaceous-fennel
California Annual Grasslands Alliance	Herbaceous-non-fennel

Original Classification	Vegetation as Categorized for Analysis
Giant Wildrye–Creeping Wildrye Superalliance	Herbaceous-non-fennel
Tall Temperate Perennial Graminoids	Herbaceous-non-fennel
Coastal Salt Pan	Herbaceous-non-fennel
Needlegrass	Herbaceous-non-fennel
Silver Beachbur-Beach Sand-Verbena Alliance	Herbaceous-non-fennel
Harding Grass	Herbaceous-non-fennel
Tidally Flooded Grasslands	Herbaceous-non-fennel
Saltgrass Alliance	Herbaceous-non-fennel
Tall Temperate Forblands	Herbaceous-non-fennel
Sea Blite-San Miguel Island Locoweed	Herbaceous-non-fennel
Tejon Mild Aster-(Coastal Goldenbush)	Herbaceous-non-fennel
Bracken Fern Alliance	Herbaceous-non-fennel
Land Use─Sparsely or Unvegetated	
Built-up	Other
Agriculture	Other
Sparsely Vegetated or Unvegetated Areas	Sparse Vegetation
Landslides	Sparse Vegetation
Cliffs-Rock Outcrops-Steep Eroded Slopes	Sparse Vegetation
Stream Beds and Flats	Sparse Vegetation
Water	Other
Planted Trees and Shrubs	Other
Unknown	Other

Results and Discussion

Existing Trapping Protocols

The current trapping protocol on Santa Cruz Island includes an extensive set of transects placed along roads, trails, ridge-tops, and canyon bottoms, which has been trapped since 2001. Assuming a 600-m effective trap radius around each trap, the current protocol samples approximately 45% of the island (Map 8-1).

Trapped areas have significantly lower slope than island-wide areas. However, this statistical significance may not have biological significance, since slope values at island-wide points are only slightly higher than at points in trapped areas, with a difference of <2° in median slopes (Table E-2). In addition, distributions of the two datasets do not show obvious differences (Figure E-1). Ruggedness values at random points did not differ between island and trapped areas (Table E-2, Figure E-2).

Trapped areas are significantly farther from the shoreline than island-wide areas (Table E-2, Figure E-3), but this difference is relatively small (<250 m if means are compared) in relation to fox movement patterns and may, therefore, not have biological relevance.

Areas sampled by the existing protocol are significantly closer to roads and to developed areas than island-wide areas, with trapped and island-wide areas differing by 700-1,100 m on average (Table E-2). Distributions of these measures show that areas within a few hundred meters of roads and within approximately 1 km of developed areas are over-sampled (Figures E-4 and E-5). This is not surprising since most trapping transects are located along roads, and developed areas are associated with roads. It is possible that these differences may have biological significance and may influence density estimates. For example, density estimates may be influenced if, for example, foxes experience higher mortality near roads, if they use roads as travel routes, or if they are attracted to or avoid developed areas. Future research on habitat selection relative to distance to roads and developed areas should examine whether this difference would bias density and abundance estimates, and whether this bias would be low or high.

The existing trapping protocol samples all vegetation categories on the island (based on our collapsed categories) but does not sample them in proportion to their availability on the island (Chi-square = 358.46, df = 6, p <0.01), due primarily to under-sampling of deciduous shrublands and over-sampling of evergreen shrublands (Figure E-6).

Table E-2. Comparison of habitat attributes on Santa Cruz Island (n = 5,000 random points) versus areas trapped with the current trapping protocol (n = 5,000 random points).

Habitat Measure	**Island Mean (sd)**	**Trapped Area Mean (sd)**	**Island Median**	**Trapped Area Median**	***Z***	***p***
Slope (degrees)	19.82 (9.06)	17.88 (8.50)	19.79	17.84	-10.75	<0.001
Ruggedness Index	0.054 (0.059)	0.053 (0.055)	0.032	0.033	-0.65	0.513
Dist. to Shore (m)	1707.3 (1275.1)	1943.5 (1357.3)	1422.5	1584.3	-8.66	<0.001
Dist. to Roads (m)	2151.8 (1715.5)	1380.4 (1581.9)	1800.6	677.8	-25.85	<0.001
Dist. to Developed (m)	2974.2 (1809.5)	2161.8 (1659.8)	2810.6	1626.1	-23.34	<0.001

Scenario A

Proposed trapping Scenario A includes 24 units made up of 12 traps each (with a configuration of 2x6 traps). Assuming a 600-m effective trap radius around each trap, Scenario A samples approximately 25% of the island (Map 8-5). Scenario A is similar to the existing protocol in that it tends to sample areas with lower slope, but with similar ruggedness, as the island (Table E-3, Figures E-1 and E-2). As discussed in relation to the existing protocol, the small absolute difference in mean and median slopes may not have relevance to fox trapping. This scenario also samples areas that are closer to roads and developed areas than are island-wide areas, but differs from the existing protocol in that sampled areas are closer to the shore than are island-wide areas (Table E-3, Figures E-3, E-4, and E-5). These differences are relatively small, however, with island-wide and sampled areas differing by <400 m for all three measures (regardless of whether means or medians are examined). It is not known if this difference has biological relevance, and we suggest that future research on habitat use and selection should examine whether this could bias trap results.

Proposed trapping Scenario A samples all the vegetation categories used in this analysis, but does not sample them in proportion to their availability on the island (Chi-square = 277.49, df=6, p <0.01). This scenario tends to under-sample deciduous shrublands and forests/woodlands-non-conifer, and over-sample evergreen shrublands, forests/woodlands-conifer, and non-fennel herbaceous areas (Figure E-7).

Table E-3. Comparison of habitat attributes on Santa Cruz Island (n = 5,000 random points) versus areas trapped with trapping Scenario A (n = 5,000 random points).

Habitat Measure	Island Mean (sd)	Trapped Area Mean (sd)	Island Median	Trapped Area Median	*Z*	*p*
Slope (degrees)	19.82 (9.06)	17.39 (8.21)	19.79	16.98	-13.63	<0.001
Ruggedness Index	0.054 (0.059)	0.052 (0.055)	0.032	0.032	-1.31	0.191
Dist. to Shore (m)	1707.3 (1275.1)	1592.7 (1246.8)	1422.5	1204.9	-4.72	<0.001
Dist. to Roads (m)	2151.8 (1715.5)	2055.9 (1793.9)	1800.6	1571.8	-4.24	<0.001
Dist. to Developed (m)	2974.2 (1809.5)	2677.5 (1832.9)	2810.6	2437.4	-8.83	<0.001

Scenario B

Proposed trapping Scenario B includes 18 units made up of 12 traps each (with a configuration of 2x6 traps). Assuming a 600-m effective trap radius around each trap, Scenario B samples approximately 19% of the island (Map 8-6). Scenario B samples areas with lower slope and lower ruggedness than island-wide areas (Table E-4, Figures E-1 and E-2). As discussed in relation to the existing protocol and Scenario A, however, the small absolute difference in mean and median slopes may not have relevance to fox trapping. The absolute differences in ruggedness are extremely small compared to the range of the ruggedness index, which has a value of 0 for completely flat terrain and a value of 1 for extremely rugged terrain, suggesting that this statistical difference may also not have biological relevance.

Areas sampled with this scenario are significantly closer to roads than are island-wide areas (Table E-4), but island-wide and sampled areas differed by <250 m (regardless of whether means or medians are examined), suggesting that this difference may not have biological relevance. Areas sampled by Scenario B did not differ statistically from island-wide areas in distance to the shore or in distance to developed areas.

Proposed trapping Scenario B samples all the vegetation categories used in this analysis, but does not sample them in proportion to their availability on the island (Chi-square = 377.35, df=6, p <0.01). This scenario also tends to under-sample deciduous shrublands and forests/woodlands-non-conifer, and over-sample evergreen shrublands, forests/woodlands-conifer, and herbaceous areas (Figure E-8).

Table E-4. Comparison of habitat attributes on Santa Cruz Island (n = 5,000 random points) versus areas trapped with trapping Scenario B (n = 5,000 random points).

Habitat Measure	Island Mean (sd)	Trapped Area Mean (sd)	Island Median	Trapped Area Median	*Z*	*p*
Slope (degrees)	19.82 (9.06)	17.19 (8.03)	19.79	16.83	-14.72	<0.001
Ruggedness Index	0.054 (0.059)	0.049 (0.054)	0.032	0.030	-3.40	0.001
Dist. to Shore (m)	1707.3 (1275.1)	1716.2 (1317.7)	1422.5	1380.3	-0.39	0.690
Dist. to Roads (m)	2151.8 (1715.5)	2362.0 (1878.8)	1800.6	2031.6	-4.41	<0.001
Dist. to Developed (m)	2974.2 (1809.5)	3025.9 (1833.4)	2810.6	2979.4	-1.15	0.248

Conclusions

Areas sampled by all three trapping scenarios have lower slope than island-wide areas, and Scenario B sampled areas with lower ruggedness. This is not surprising, since logistic and safety constraints required that traps were not placed in steep and rugged terrain. These differences may not have an influence on trap result, however, because absolute differences were small, as discussed above (Tables E-2, E-3, and E-4). The existing trapping protocol and Scenario A both sample areas that differ from island-wide areas in distance to the shore but the absolute differences are small relative to fox movement patterns and may, therefore, not have biological relevance. Although all three trapping scenarios sampled areas closer to roads (as was expected, as traps were placed in proximity to roads for logistic reasons) and to developed areas, compared to island-wide areas, this difference was most extreme in the existing protocol (Table E-2). It is possible that this biases trap results, if foxes select or avoid areas close to roads and developed areas. We therefore suggest that radiocollared foxes should be used to examine patterns of habitat use and selection, to determine if such difference might bias trap results. Although all three trap scenarios did not sample vegetation categories in proportion to their availability on the island, Scenario A sampled these most adequately. Again, habitat selection studies would provide data useful to understanding potential biases associated with these differences.

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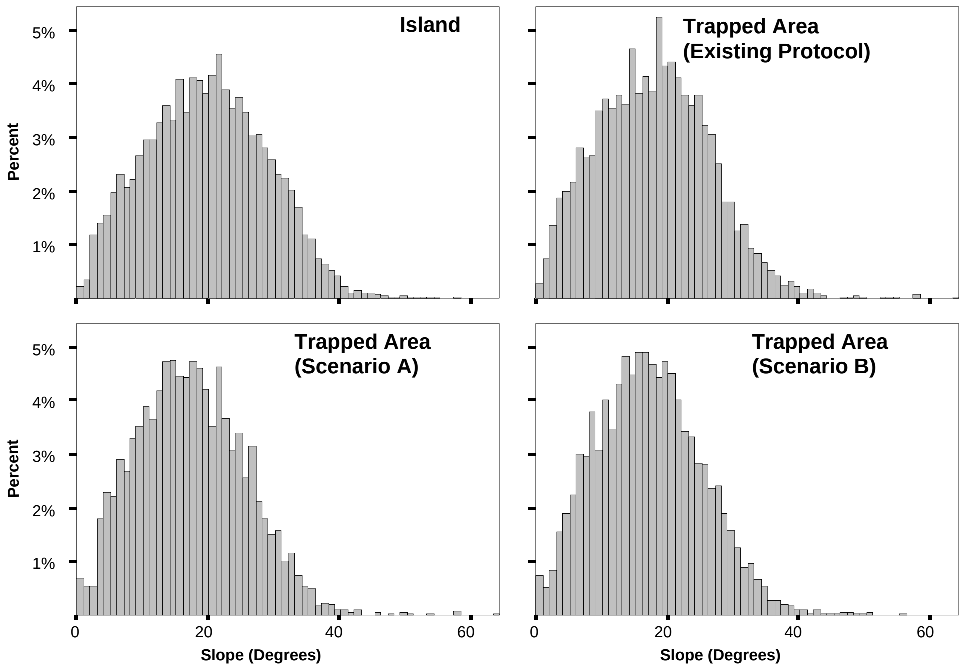

Figure E-1. Distribution of slope (as percent of random points) on Santa Cruz Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario A, and Scenario B).

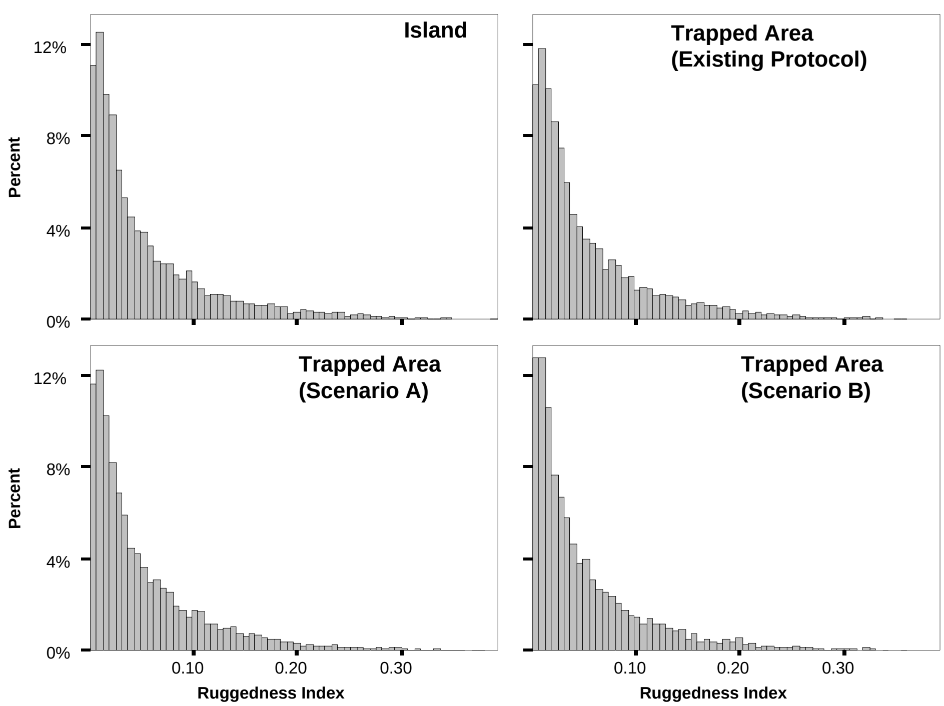

Figure E-2. Distribution of ruggedness (as percent of random points) on Santa Cruz Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario A, and Scenario B).

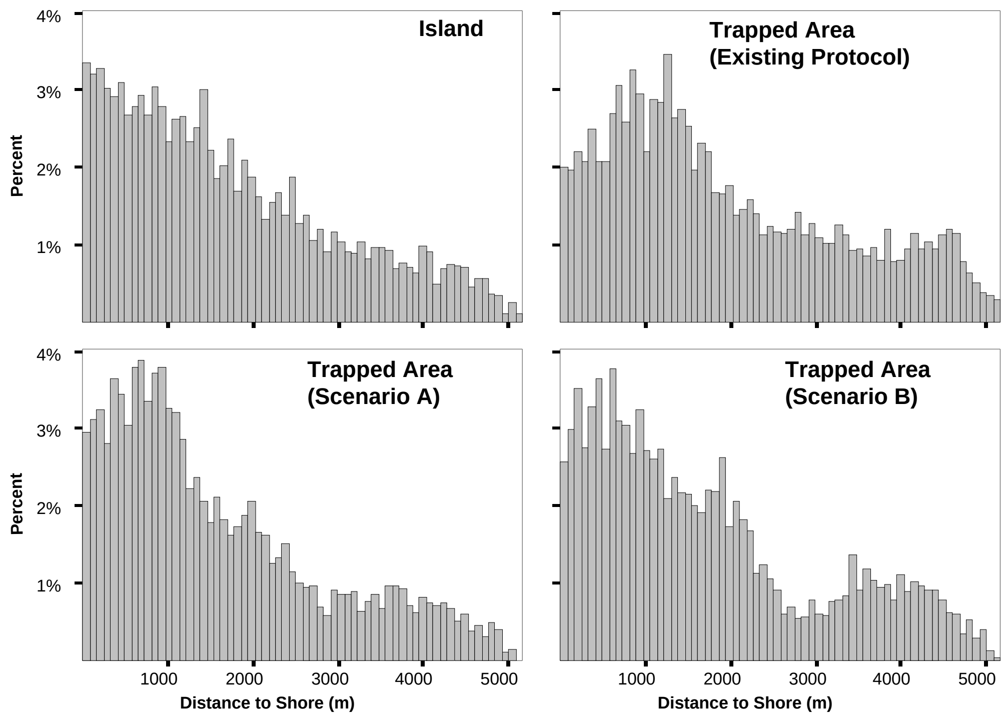

Figure E-3. Distribution of distance to shore (as percent of random points) on Santa Cruz Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario A, and Scenario B).

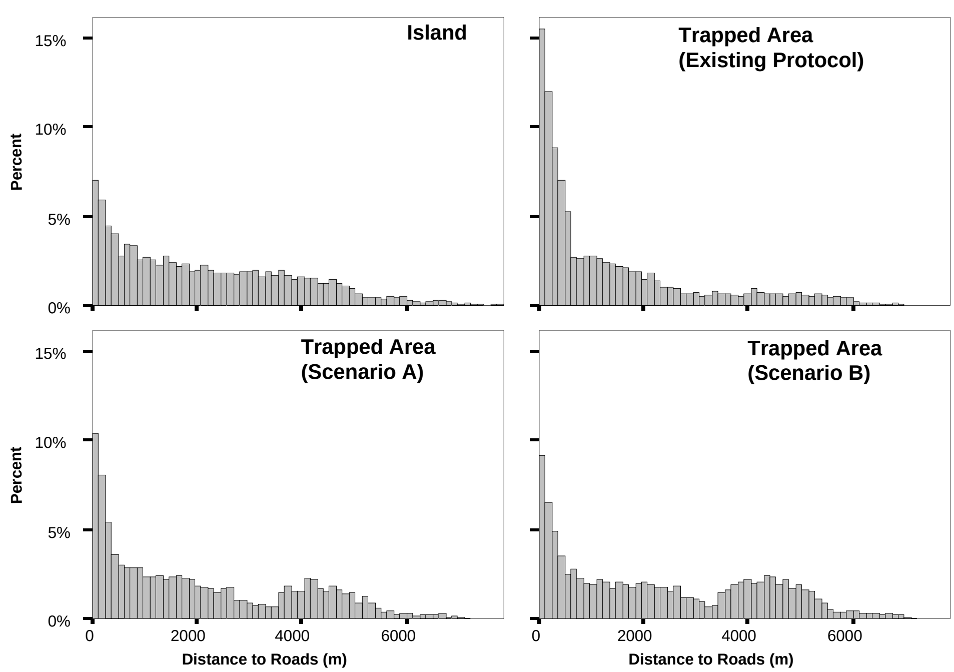

Figure E-4. Distribution of distance to roads (as percent of random points) on Santa Cruz Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario A, and Scenario B).

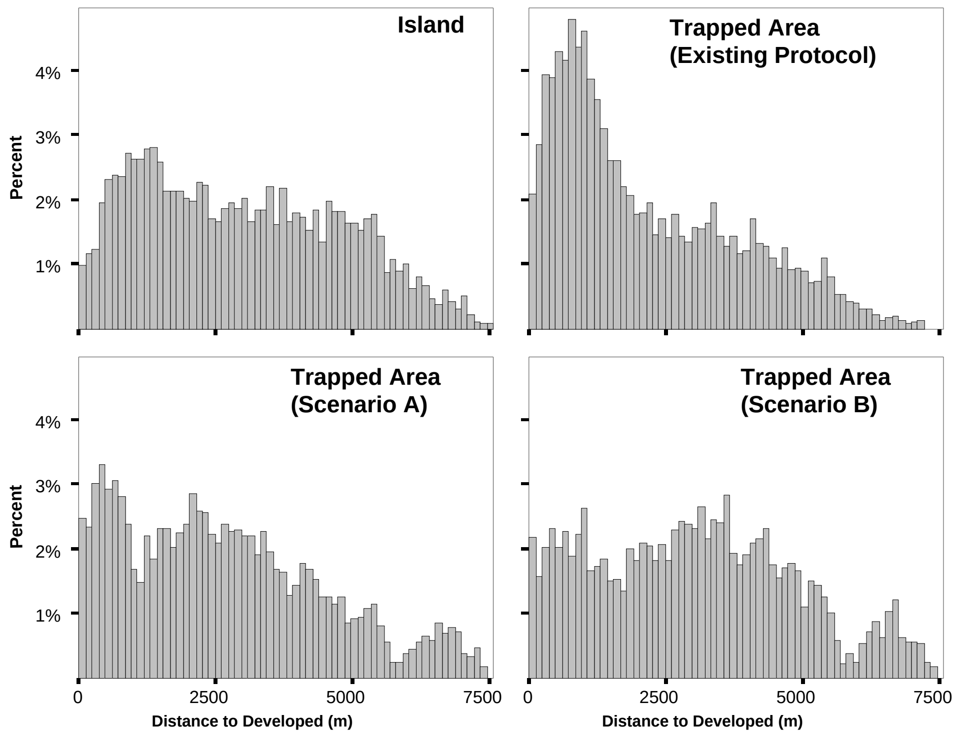

Figure E-5. Distribution of distance to developed areas (as percent of random points) on Santa Cruz Island versus in areas trapped with three trapping scenarios (Existing Protocol, Scenario A, and Scenario B).

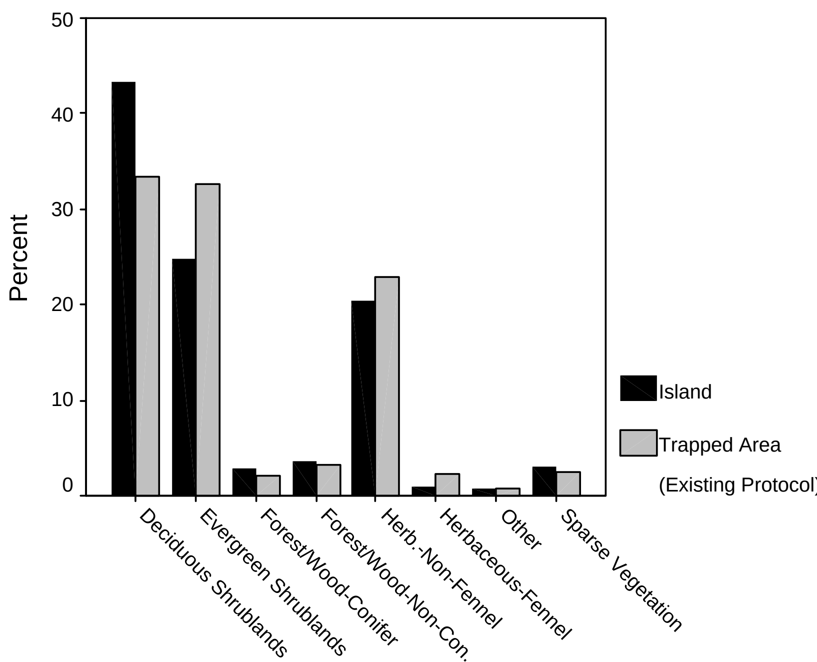

Figure E-6. Distribution of vegetation types (as percent of random points) on Santa Cruz Island versus in areas trapped with Existing Protocol.

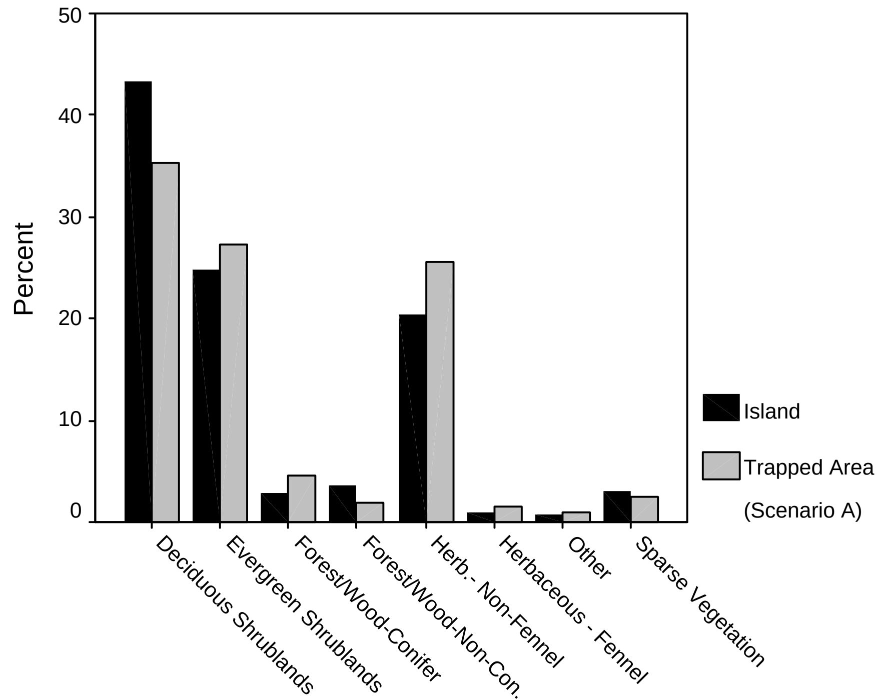

Figure E-7. Distribution of vegetation types (as percent of random points) on Santa Cruz Island versus in areas trapped with trapping Scenario A.

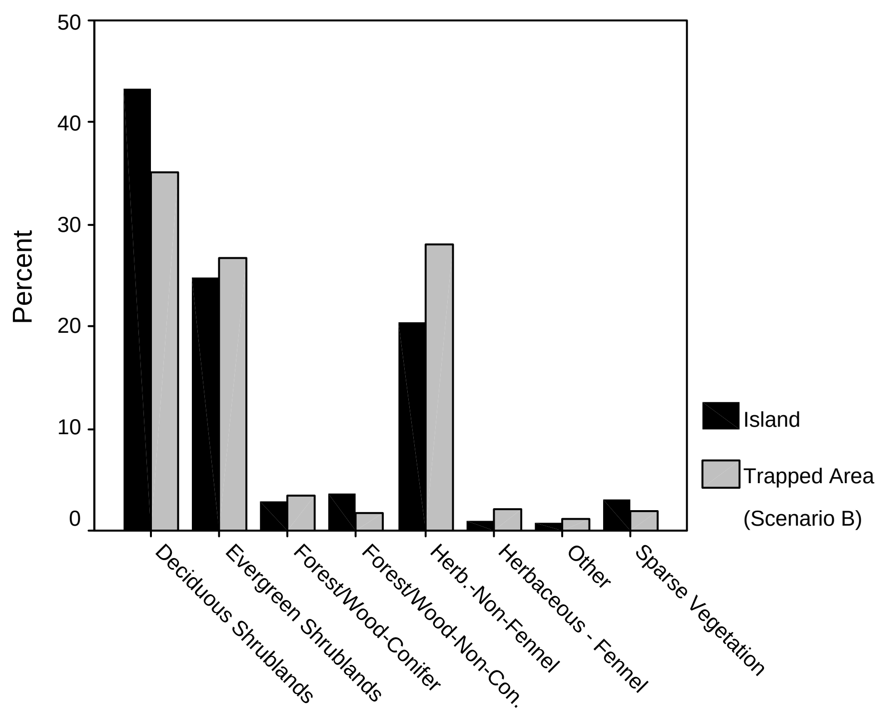

Figure E-8. Distribution of vegetation types (as percent of random points) on Santa Cruz Island versus in areas trapped with trapping Scenario B.

APPENDICES F–J

Prepared by

Vickie J. Bakker

Appendix F

Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on San Miguel Island

Introduction

The monitoring plan in the main body of this report proposes a new design for mark-recapture trapping of island foxes on San Miguel Island to increase the efficiency and robustness of monitoring efforts and to achieve new monitoring goals. Under this plan, trapping would consist of a dispersed set of small trapping units (2x6 traps or 5x6 traps). Historically, island foxes have been trapped using mark-recapture trapping methods with traps arrayed in some type of grid formation. This appendix uses multivariate statistical methods to evaluate the degree to which current and proposed trapping locations sample the range of variation on the island for features hypothesized to be important to foxes. The intent of this analysis is to add to the interpretations of the univariate representation analyses by using principal components analysis (PCA) to focus on groups of habitat attributes that tend occur together.

Methods

Six continuous variables were identified as likely to influence fox habitat quality on San Miguel Island─slope, ruggedness, distance to trails, distance to human development, distance to shoreline, and distance to freshwater. These habitat characteristics were extracted from a GIS at randomly located points at a density of ~144 points/km^2), and trapped areas (existing and proposed) were sampled similarly. Trapped areas were defined as all locations within a 600-m buffer of a trap station. The buffer was added to characterize the entire area likely to be used by foxes entering traps including areas used by foxes living adjacent to grids and captured in perimeter traps. The 600-m buffer is equal to 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. Additional details on methods of habitat characterization for San Miguel Island can be found in Appendix A.

To compare the multivariate attributes of trapped areas to those of the entire island, I performed a principal components analysis (SAS Proc Princomp; SAS Institute Inc. 2005) on the island-wide habitat data and compared mean principal component scores for trapped areas to those of island-wide areas overall and by vegetation type. The latter analysis was performed to assess whether the representativeness of trapped areas was influenced by sampling targeted at certain vegetation types that might have biased habitat characteristics. Variables were mean-centered and standardized prior to conducting the PCA (i.e., PCA used the correlation matrix). To allow a visual assessment of the habitat sampled by the trapped areas, I plotted the mean PC scores for both trapped and island-wide areas. I focus on detecting and describing the major differences in the attributes of trapped areas compared to the islands as a whole as evidenced by separation of 95% confidence intervals on the mean PC scores (while recognizing that separation of confidence intervals is a conservative metric for assessing difference (Schenker and Gentleman

2001). Habitat variables were transformed as necessary to achieve approximately normal distributions to improve the normality of PC scores, which is assumed when using PC scores for hypothesis tests. See Figure J-1 in Appendix J for an example of how PCA classifies multivariate habitat types.

PCA identifies patterns within multivariate data, eliminates correlation among data, and reduces the dimensionality of multivariate data to simplify analyses. PCA can add to univariate assessments of representation by focusing on groups of habitat attributes that tend occur together, such as steep rugged shoreline, thereby refining the types of areas that are under or overrepresented.

Results and Discussion

PCA interpretations. Nearly 40% of the variation in terrain variables is accounted for by the first principal component, which is more than twice the second principal component. Use of four PCs can describe the island and trapping areas thoroughly (Table F-1).

Table F-1. Eigenvalues of the correlation matrix for PCA on terrain attributes on San Miguel Island.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	2.4	0.393	0.393
2	1.1	0.182	0.575
3	1.0	0.162	0.737
4	0.8	0.126	0.862
5	0.5	0.083	0.946
6	0.3	0.054	1.000

PC1 is represents areas that are steep and rugged, close to shoreline, and far from trails and development, referred to here as "Remote shoreline." PC2 is characterizes areas that are far from freshwater drainages and far from developed areas, referred to as "Dry remote terrain." PC3 represents areas that are close to freshwater drainages but far from trails and development, referred to as "Off-trail remote drainages." Finally, PC4 is heavily influenced by areas far from development and shoreline but close to trails and is referred to as "Remote interior trails."

Table F-2. Eigenvectors for PCA on terrain attributes on San Miguel Island.

	Principal Component 1	2	3	4
	Steep rugged off-trail shoreline	**Dry remote terrain**	**Off-trail remote drainages**	**Remote interior trails**
Slope[1]	0.52	-0.26	-0.23	0.20
Ruggedness[2]	0.51	-0.26	-0.27	0.30
Distance to…				
Trails[3]	0.40	0.21	0.48	-0.53
Development[3]	0.29	0.48	0.51	0.60
Shoreline[3]	-0.47	-0.15	0.21	0.47
Freshwater[2]	-0.03	0.75	-0.59	0.04

[1] Cube-root transformed [2] ln transformed [3] Square-root transformed

Representation analysis using PCA

Overall. Both the large grids of the 1990s and the current small grids under-represent all PCs, under-sampling steep rugged remote shoreline (PC1), remote areas far from drainages (PC2), remote drainages far from trails (PC3), and remote trails in the interior (PC4, Figure F-1). Proposed Scenario B similarly under-samples steep remote shoreline but is unbiased with respect to all other multivariate habitat types except for remote interior trails, which are over-sampled. Finally, proposed Scenario C adequately represents most multivariate habitat types including steep rugged remote shoreline but under-samples terrain far from drainages and development, such as those found near the center of the island.

By vegetation type. Existing grids under-sample steep rugged off-trail shoreline (PC1) and dry remote terrain (PC2) for all vegetation type except for grassland habitats, where recent grids better sample these habitat complexes (Figure F-2). In contrast, both proposed scenarios sample more atypical grassland habitat on PC1 (Figure F-3). Scenario B under-samples steep rugged off-trail shoreline across vegetation types, while Scenario C displays less bias within each vegetation type and none in *Haplopappus* scrub resulting in no bias overall. The opposite situation occurs with dry remote terrain, where Scenario B generally displays less sampling bias within each habitat type, resulting in no overall bias.

Conclusions

Both the large grids of the 1990s and the current 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 results 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.

Literature Cited

SAS Institute Inc. 2005. SAS/STAT user's guide. Release 8.02 edition. SAS Institute, Inc., Cary, NC.

Schenker, N., and J.F. Gentleman. 2001. On judging the significance of differences by examining the overlap between confidence intervals. The American Statistician **55**:182-186.

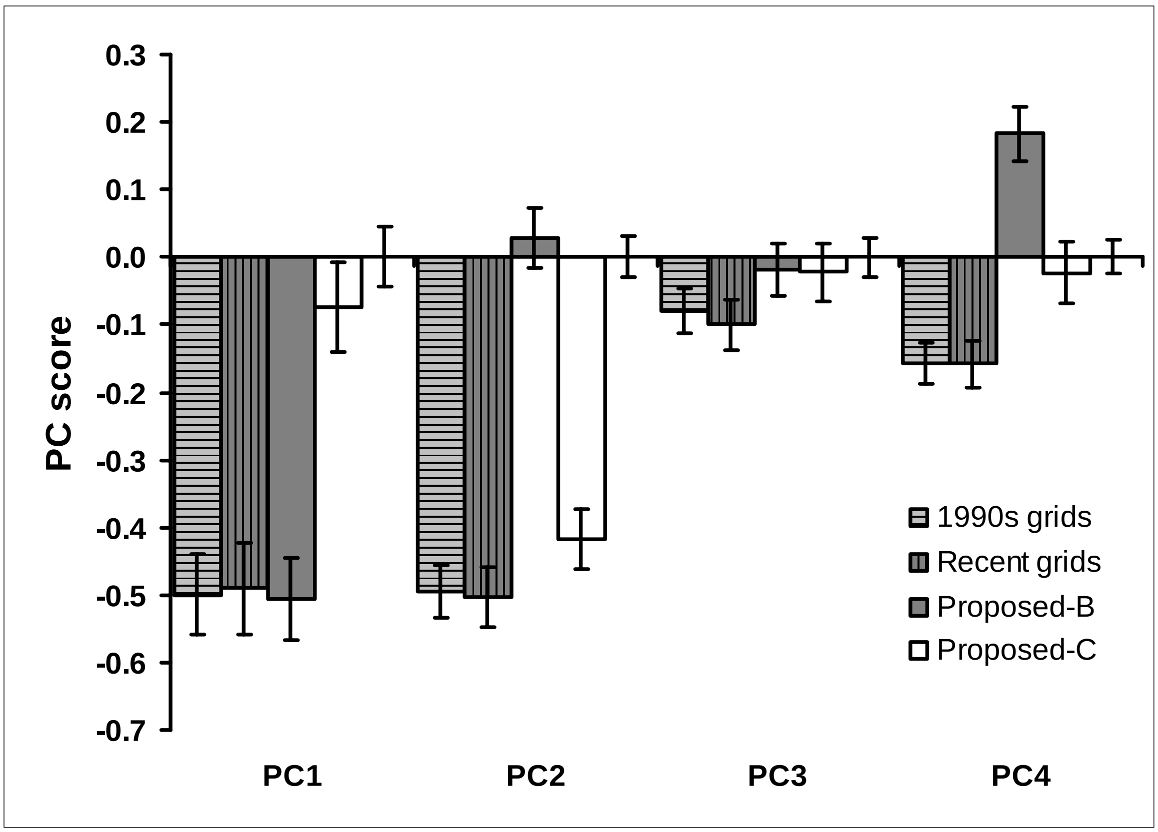

Figure F-1: Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas trapped for island foxes with large grids in the 1990s, with recent smaller grids, and with proposed trapping Scenarios B and C. Also shown are confidence intervals for island-wide PC scores; the island-wide mean for each PC is 0 because PCA was performed on island data and variables were mean centered and standardized prior to analysis. PC1 is remote shoreline areas, PC2 is dry remote terrain, and PC3 is off-trail remote drainages. PC4 is remote interior trails.

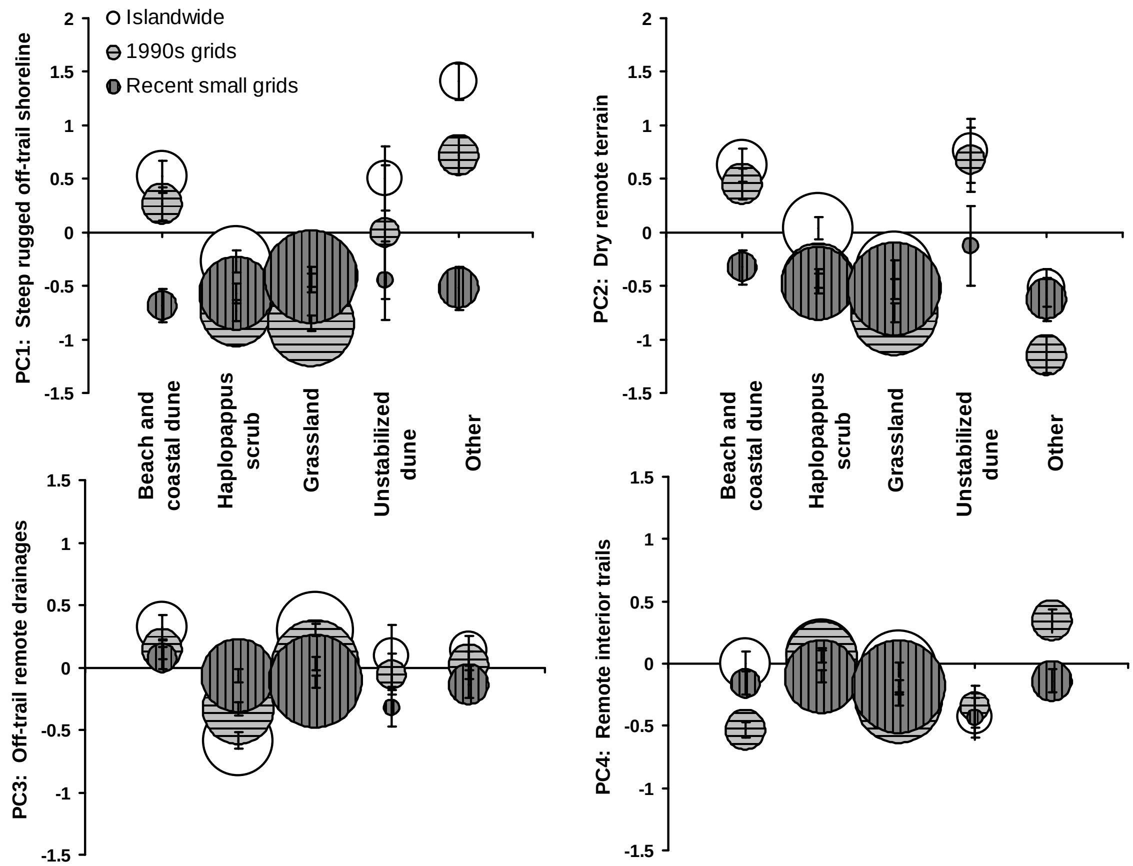

Figure F-2. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas in areas trapped for island foxes with large grids in the 1990s and with recent smaller grids relative to the entire island by vegetation type. Marker size is weighted by proportional coverage of each vegetation type.

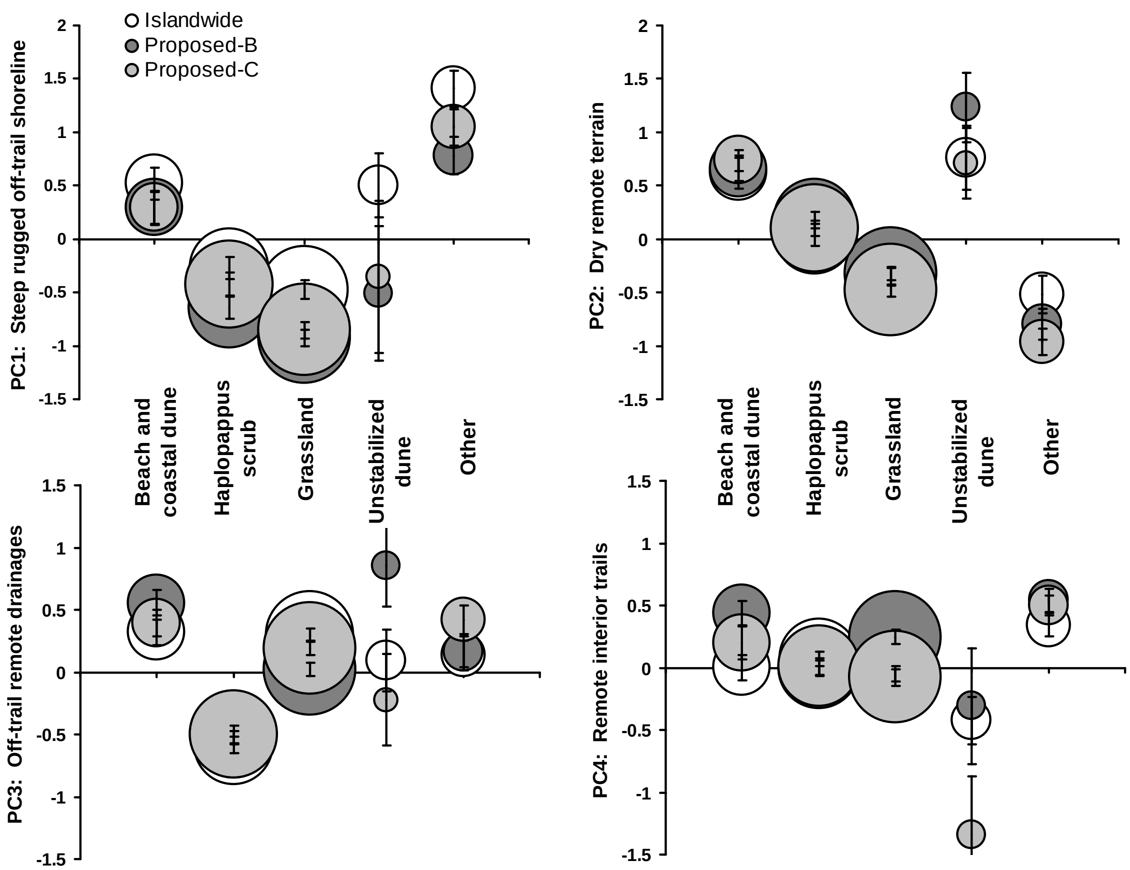

Figure F-3. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenarios B and C grids relative to the entire island by vegetation type. Marker size is weighted by proportional coverage of each vegetation type.

Appendix G

Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on San Nicolas Island

Introduction

The monitoring plan in the main body of this report proposes a new design for mark-recapture trapping of island foxes on San Nicolas Island to increase the efficiency and robustness of monitoring efforts and to achieve new monitoring goals. Under this plan, trapping would consist of a dispersed set of small trapping units (2x6 traps or 6x6 traps). Historically, island foxes have been trapped using mark-recapture trapping methods with traps arrayed in large grids. This appendix uses multivariate statistical methods to evaluate the degree to which current and proposed trapping locations sample the range of variation on the island for features hypothesized to be important to foxes. The intent of this analysis is to add to the interpretations of the univariate representation analyses by using principal components analysis (PCA) to focus on groups of habitat attributes that tend occur together.

Methods

Six continuous variables were identified as likely to influence fox habitat quality on San Nicolas Island─slope, ruggedness, distance to trails, distance to human development, distance to shoreline, and distance to freshwater. These habitat characteristics were extracted from a GIS at randomly located points at a density of ~144 points/km^2), and trapped areas (existing and proposed) were sampled similarly. Trapped areas were defined as all locations within a 600-m buffer of a trap station. The buffer was added to characterize the entire area likely to be used by foxes entering traps including areas used by foxes living adjacent to grids and captured in perimeter traps. The 600-m buffer is equal to 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. Additional details on methods of habitat characterization for San Nicolas Island can be found in Appendix B.

To compare the multivariate attributes of trapped areas to those of the entire island, I performed a principal components analysis (SAS Proc Princomp; SAS Institute Inc. 2005) on the island-wide habitat data and compared mean principal component scores for trapped areas to those of island-wide areas overall and by vegetation type. The latter analysis was performed to assess whether the representativeness of trapped areas was influenced by sampling targeted at certain vegetation types that might have biased habitat characteristics. Variables were mean-centered and standardized prior to conducting the PCA (i.e., PCA used the correlation matrix). To allow a visual assessment of the habitat sampled by the trapped areas, I plotted the mean PC scores for both trapped and island-wide areas. I focus on detecting and describing the major differences in the attributes of trapped areas compared to the islands as a whole as evidenced by separation of 95% confidence intervals on the mean PC scores (while recognizing that separation of confidence intervals is a conservative metric for assessing difference (Schenker and Gentleman

2001). Habitat variables were transformed as necessary to achieve approximately normal distributions to improve the normality of PC scores, which is assumed when using PC scores for hypothesis tests. See Figure J-1 in Appendix J for an example of how PCA classifies multivariate habitat types.

PCA identifies patterns within multivariate data, eliminates correlation among data, and reduces the dimensionality of multivariate data to simplify analyses. PCA can add to univariate assessments of representation by focusing on groups of habitat attributes that tend occur together, such as steep rugged shoreline, thereby refining the types of areas that are under or overrepresented.

Results and Discussion

PCA interpretations. Nearly 50% of the variation in the terrain variable is accounted for by the first principal component. Using three or four PCs describes the island thoroughly (Table G-1).

Table G-1. Eigenvalues of the correlation matrix for PCA on habitat attributes on San Nicolas Island.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	2.907	0.485	0.485
2	1.268	0.211	0.696
3	0.742	0.124	0.820
4	0.503	0.084	0.903
5	0.300	0.050	0.953
6	0.280	0.047	1.000

PC1 contained approximately equal loadings from all variables, and thus it represents areas that are steep and rugged, far from paved roads, development and freshwater but close to shoreline (Table G-2), referred to here as “Dry steep rugged remote shoreline.” PC2 accounts for steep and rugged terrain near freshwater sources, labeled here as “Steep rugged drainages.” PC3 represents areas far from paved roads, development, and shoreline but close to freshwater, referred to as “Remote interior drainages.” Finally, PC4 represents lands far from shoreline and freshwater and is labeled “Dry interior.”

Table G-2. Eigenvectors for PCA on habitat attributes on San Nicolas Island.

	Principal Component			
	1	2	3	4
	Dry steep rugged remote shoreline	**Steep rugged drainages**	**Remote interior drainages**	**Dry interior**
Slope[1]	0.36	0.61	-0.02	0.17
Ruggedness[1]	0.38	0.57	-0.19	-0.01
Distance to…				
Paved roads[2]	0.48	-0.21	0.39	0.02
Development[3]	0.45	-0.19	0.59	-0.07
Shoreline[3]	-0.41	0.24	0.50	0.70
Freshwater[3]	0.37	-0.41	-0.46	0.68

[1]ln transformed [2] Cube-root transformed [3] Square-root transformed

Representation analysis using PCA

Overall. Existing grid trapping has underrepresented PC1 and modestly overrepresented PC4 (Figure G-1). Thus, dry rugged remote shoreline is under-sampled, although once accounting for topography linked to proximity to shoreline and development, steep and rugged terrain is not under-sampled (PC2, Figure G-1). Interior areas far from drainages are somewhat over-sampled (PC4, Figure G-1). Proposed trapping scenarios under-represent steep and rugged terrain of all types (PC1 and PC2) and modestly over-represent interior terrain of all types (PC3 and 4, Figure G-1). Scenario C appears to do a slightly better overall job representing multivariate habitat types on the island.

By vegetation type. Trapping areas appear to sample the major vegetation types roughly in proportion to their occurrence on the island, although *Coreopsi*s vegetation is clearly under-sampled (Figure G-2). Within each vegetation type, trapping grids consistently under-represent PC1 and over-represent PC4, similar to overall island-wide patterns (Figure G-2). Interestingly, the lack of bias in sampling PC2 and PC3 arises partly from positive and negative biases within many vegetation types, although there was no bias for coast scrub, the most extensive vegetation type.

Proposed Scenarios B and C appear to sample the major vegetation types roughly in proportion to their occurrence on the island including better representation of *Coreopsis* vegetation (Figure G-3). Within major vegetation types, both proposed trapping scenarios generally under-represent PC1 and PC2 and over-represent PC3 and 4, similar to overall island-wide patterns (Figure G-3). However, Scenario C represents barren vegetation with little bias with respect to rough remote shoreline (PC1), and Scenario B adequately represents steep rugged drainages in barren vegetation types.

Conclusions

Existing grid trapping has underrepresented dry rugged remote shoreline, although once accounting for topography linked to proximity to shoreline and development, steep and rugged terrain was not under-sampled. Interior areas far from drainages are currently somewhat over-sampled. Proposed trapping scenarios under-represent steep and rugged terrain of all types, and modestly over-represent interior terrain of all types. Overall, Scenario C appears to do a slightly better overall job representing multivariate habitat types on the island. 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. Density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to assure that these biases do not bias monitoring program results.

Literature Cited

SAS Institute Inc. 2005. SAS/STAT user's guide. Release 8.02 edition. SAS Institute, Inc., Cary, NC.

Schenker, N., and J.F. Gentleman. 2001. On judging the significance of differences by examining the overlap between confidence intervals. The American Statistician **55**:182-186.

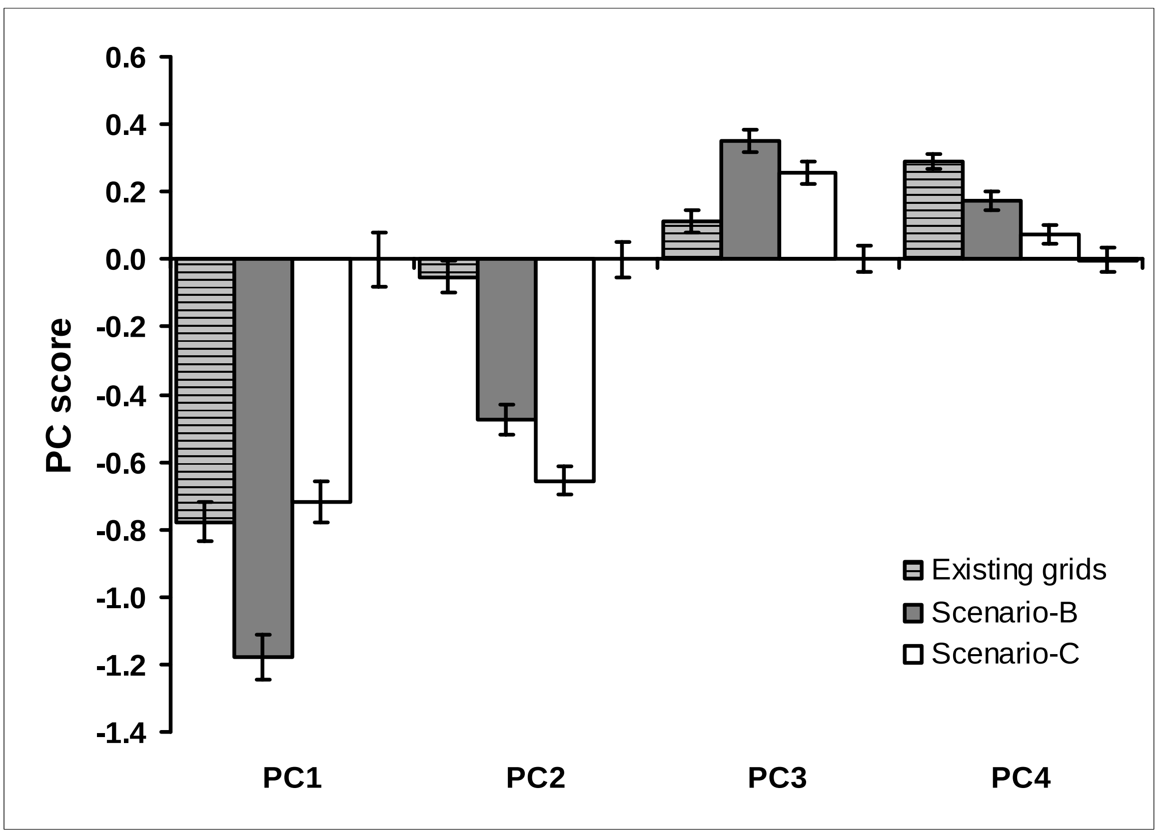

Figure G-1. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped for island foxes and those proposed for trapping under Scenarios B and C. Also shown are confidence intervals for island-wide PC scores; the island-wide mean for each PC is 0 because PCA was performed on island data and variables were mean centered and standardized prior to analysis. PC1 is dry remote rugged shoreline. PC2 is steep and rugged drainages. PC3 is remote interior drainages. PC4 is dry interior.

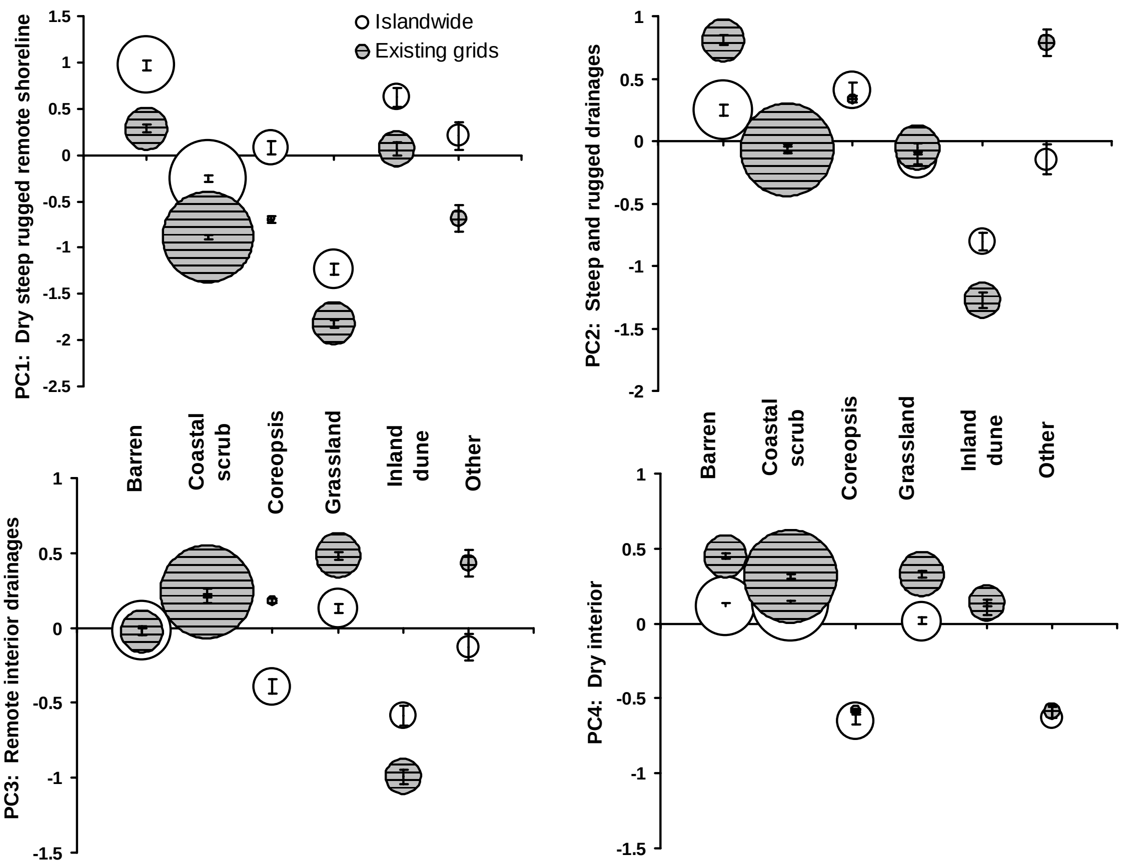

Figure G-2. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped by existing grids relative to the entire island by vegetation type for PC1-4. Marker size is weighted by proportional coverage of each vegetation type.

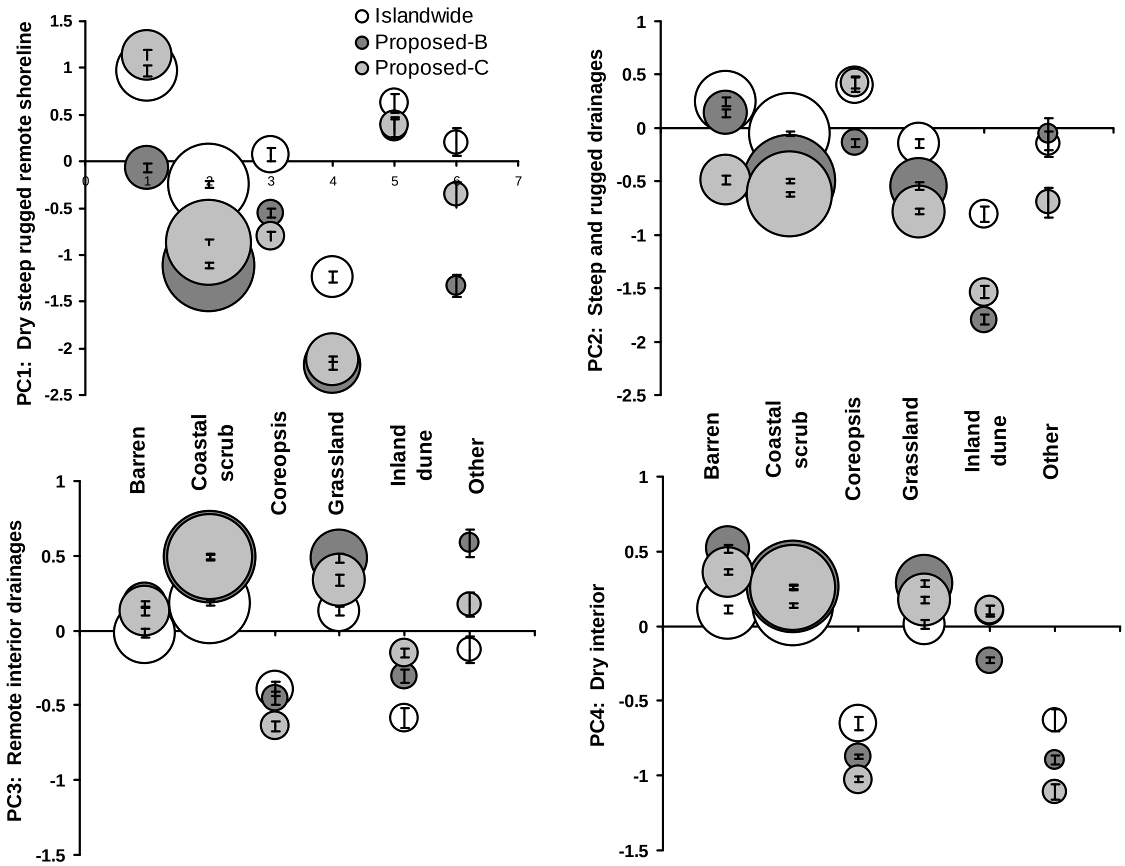

Figure G-3. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenarios B and C relative to the entire island by vegetation type for PC1-4. Marker size is weighted by proportional coverage of each vegetation type.

Appendix H

Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on Santa Catalina Island

Introduction

The monitoring plan in the main body of this report proposes a new design for mark-recapture trapping of island foxes on Santa Catalina Island to increase the efficiency and robustness of monitoring efforts and to achieve new monitoring goals. Under this plan, trapping would consist of a dispersed set of small trapping units (2x6 traps). Historically, island foxes have been trapped using mark-recapture trapping methods with traps arrayed in single line transects throughout Santa Catalina Island. This appendix uses multivariate statistical methods to evaluate the degree to which current and proposed trapping locations sample the range of variation on the island for features hypothesized to be important to foxes. The intent of this analysis is to add to the interpretations of the univariate representation analyses by using principal components analysis (PCA) to focus on groups of habitat attributes that tend occur together.

Methods

Because foxes in the areas west of Two Harbors on Santa Catalina Island are considered to be an isolated population, separate sampling plans are proposed for eastern and western parts of the island. Thus, two separate analyses of representativeness were conducted. Six continuous variables were identified as likely to influence fox habitat quality on the East End of Santa Catalina Island─slope, ruggedness, distance to paved roadways, distance to human development, distance to freshwater, and distance to shoreline. Distances to freshwater and paved roads were not considered for the West End of Santa Catalina Island because neither freshwater nor paved roads were found there. These habitat characteristics were extracted from a GIS at randomly located points at a density of ~144 points/km^2), and trapped areas (existing and proposed) were sampled similarly. Trapped areas were defined as all locations within a 600-m buffer of a trap station. The buffer was added to characterize the entire area likely to be used by foxes entering traps including areas used by foxes living adjacent to grids and captured in perimeter traps. The 600-m buffer is equal to 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. Additional details on methods of habitat characterization for Santa Catalina Island can be found in Appendix C.

To compare the multivariate attributes of trapped areas to those of the entire island, I performed a principal components analysis (SAS Proc Princomp; SAS Institute Inc. 2005) on the island-wide habitat data and compared mean principal component scores for trapped areas to those of island-wide areas overall and by vegetation type. The latter analysis was performed to assess whether the representativeness of trapped areas was influenced by sampling targeted at certain vegetation types that might have biased habitat characteristics. Variables were mean-centered and standardized prior to conducting the PCA (i.e., PCA used the correlation matrix). To allow a visual assessment of the habitat sampled by the trapped areas, I plotted the mean PC scores for both trapped and island-wide areas. I focus on detecting and describing the major differences in the attributes of trapped areas compared to the islands as a whole as evidenced by separation of 95% confidence intervals on the mean PC scores (while recognizing that separation of confidence intervals is a conservative metric for assessing difference (Schenker and Gentleman 2001). Habitat variables were transformed as necessary to achieve approximately normal distributions to improve the normality of PC scores, which is assumed when using PC scores for hypothesis tests.

PCA identifies patterns within multivariate data, eliminates correlation among data, and reduces the dimensionality of multivariate data to simplify analyses. PCA can add to univariate assessments of representation by focusing on groups of habitat attributes that tend occur together, such as steep rugged shoreline, thereby refining the types of areas that are under or overrepresented. See Figure J-1 in Appendix J for an example of how PCA classifies multivariate habitat types.

Results and discussion

Santa Catalina Island—East End

PCA interpretations. Four principal components accounts for 85% of the variation on the east side of the island (Table H-1).

Table H-1. Eigenvalues of the correlation matrix for PCA on habitat attributes on the East End of Santa Catalina Island.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	1.87	0.31	0.312
2	1.51	0.25	0.564
3	1.01	0.17	0.732
4	0.72	0.12	0.852
5	0.54	0.09	0.941
6	0.35	0.06	1.000

More than 30% of the variation in the habitat attributes on the East End of Santa Catalina Island is accounted for by PC1, which contained positive loadings from areas that are steep, far from freshwater and development, and close to shoreline (Table H-2). Thus PC1, which generally characterizes steep escarpments on the island's perimeter, is referred to as "Dry remote steep shoreline." PC2 accounts for smooth and level areas remote from development, and is labeled as "Remote and gentle terrain." PC3 represents rugged terrain far from shore and development and is referred to as "Remote rugged interior." Finally, PC4 represents lands that are steep but not rugged.

Table H-2. Eigenvectors for PCA on habitat attributes on the East End of Santa Catalina Island.

	Principal Component			
	1	2	3	4
	Dry remote steep shoreline	**Remote and gentle terrain**	**Remote rugged interior**	**Steep and smooth**
Slope[1]	0.36	-0.39	0.21	0.81
Ruggedness[2]	0.09	-0.43	0.70	-0.48
Distance to…				
Paved roads[3]	0.21	0.65	0.18	0.06
Development[1]	0.41	0.46	0.40	0.01
Shoreline[3]	-0.52	0.12	0.51	0.24
Freshwater[1]	0.61	-0.13	-0.13	-0.23

[1] Square-root transformed [2] ln transformed [3] Cube-root transformed

Representation analysis using PCA

Overall. Existing trapping under-represents PC1 and modestly over-represents PC2 (Figure H-1). Thus, existing trapping under-samples the island's steep escarpment far from development and tends to over-sample more gentle terrain far from development. All other habitat types appear to be well represented by current trapping. Proposed Scenarios A and B similarly under-sample PC1, the island's steep escarpment far from development. In contrast to existing trapping however, proposed scenarios significantly over-sample gentle terrain far from development and rugged interior terrain far from development, thereby indicating a general under-sampling of paved roads and development regardless of terrain type. Scenario A represents the multivariate attributes of the island modestly better than Scenario B.

By vegetation type. Both existing and proposed trapping scenarios generally sample vegetation in proportion to its occurrence. For all, trap locations within each vegetation type represent habitat attributes consistent with overall patterns (Figures H-2 and H-3). Thus, existing trap locations within each vegetation type sample atypical locations with respect to key habitat attributes, favoring locations with farther from remote shoreline and closer to remote and gentle terrain. Proposed scenarios show similar patterns but over-represent remote terrain of all types.

Santa Catalina Island—West End

PCA interpretations. Over a third of the variation in habitat attributes on the West End of Santa Catalina Island is accounted for by the first principal component (Table H-3), and three PCs characterize nearly 85% of the variation.

Table H-3. Eigenvalues of the correlation matrix for PCA on habitat attributes on the West End of Santa Catalina Island.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	1.40	0.350	0.350
2	1.03	0.257	0.607
3	0.95	0.236	0.843
4	0.63	0.157	1.000

PC1 represents areas with steep slopes far from development and is labeled "Steep and remote terrain" (Table H-4). PC2 is strongly influenced by areas far from shore and by rugged areas and is labeled "Rugged interior." PC3 represents gentle terrain, especially those lands far from development and shoreline ("Gentle remote interior").

Table H-4. Eigenvectors for PCA on habitat attributes on the West End of Santa Catalina Island.

	Principal Component		
	1	**2**	**3**
	Steep and remote terrain	**Rugged interior**	**Gentle remote interior**
Slope[1]	0.69	-0.11	0.11
Ruggedness[2]	0.29	0.48	-0.83
Distance to…			
Development[2]	0.61	0.26	0.43
Shoreline[3]	-0.27	0.83	0.35

[1] Square-root transformed [2]ln transformed [3] Cube-root transformed

<u>Representation analysis using PCA</u>

<u>*Overall.*</u> Existing transect trapping on the West End of Santa Catalina Island has modestly under-represented PC1 and has tended to over-represent the PC 2 (Figure H-4). Thus, steep terrain far from development (far from the town of Two Harbors) is under-sampled with current trapping, and there is minor over-sampling of interior areas, especially rugged interior. Proposed Scenario A (and B, which is identical) under-represents steep and remote terrain (PC1) more substantially than existing transects and over-represents gentle terrain in the remote interior (PC3) more significantly. However, the proposed scenario is unbiased with respect to rugged interior lands (PC2).

<u>*By vegetation type.*</u> Both existing and proposed scenarios generally sample vegetation in proportion to its occurrence. Avoidance of steep remote terrain by both existing and proposed

trapping scenarios appears to arise largely from avoidance of these attributes within barren and coastal sage scrub habitats (PC1, Figures H-5 and H-6). Over-sampling of rugged interior by existing transects is also most pronounced in barren and coastal sage scrub habitat. Finally overrepresentation of gentle remote interior terrain tends to occur across all habitat types.

Conclusions

On the East End of Santa Catalina Island, both existing and proposed trapping scenarios under-sample the island's steep escarpment far from development. Proposed scenarios also significantly over-sample areas far from paved roads and development regardless of slope and ruggedness. Scenario A represents the multivariate attributes of the island modestly better than Scenario B. On the West End of the island, existing and proposed trapping scenarios again under-sample steep terrain far from development, with the proposed scenario more substantially biased in this regard. Existing transects over-sample rugged interior habitat, while the proposed scenario over-samples gentle remote interior. 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. Density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to assure that monitoring program results are not biased.

Literature Cited

SAS Institute Inc. 2005. SAS/STAT user's guide. Release 8.02 edition. SAS Institute, Inc., Cary, NC.

Schenker, N., and J.F. Gentleman. 2001. On judging the significance of differences by examining the overlap between confidence intervals. The American Statistician **55**:182-186.

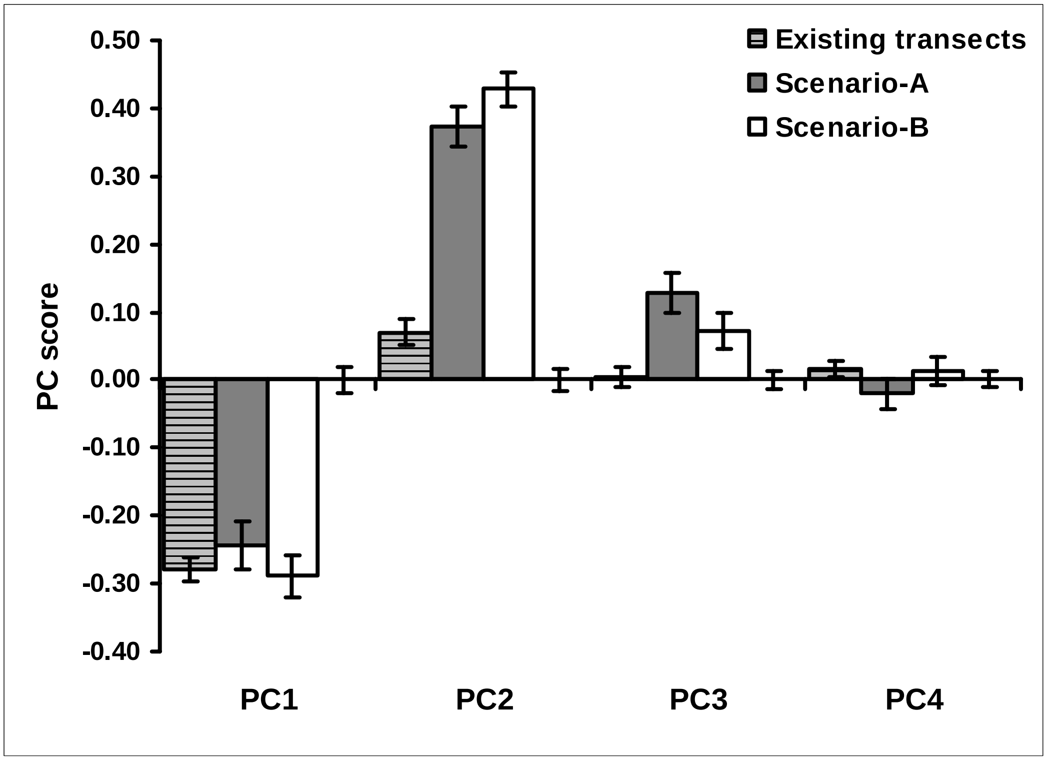

Figure H-1. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped for island foxes and those proposed for trapping under Scenarios A and B. Also shown are confidence intervals for East End (i.e., island-wide) PC scores; the island-wide mean for each PC is 0 because PCA was performed on island data and variables were mean centered and standardized prior to analysis. PC1 characterizes dry steep shoreline. PC2 is influenced by remote gentle terrain. PC3 represents remote rugged interior. PC4 is influenced by steep smooth terrain.

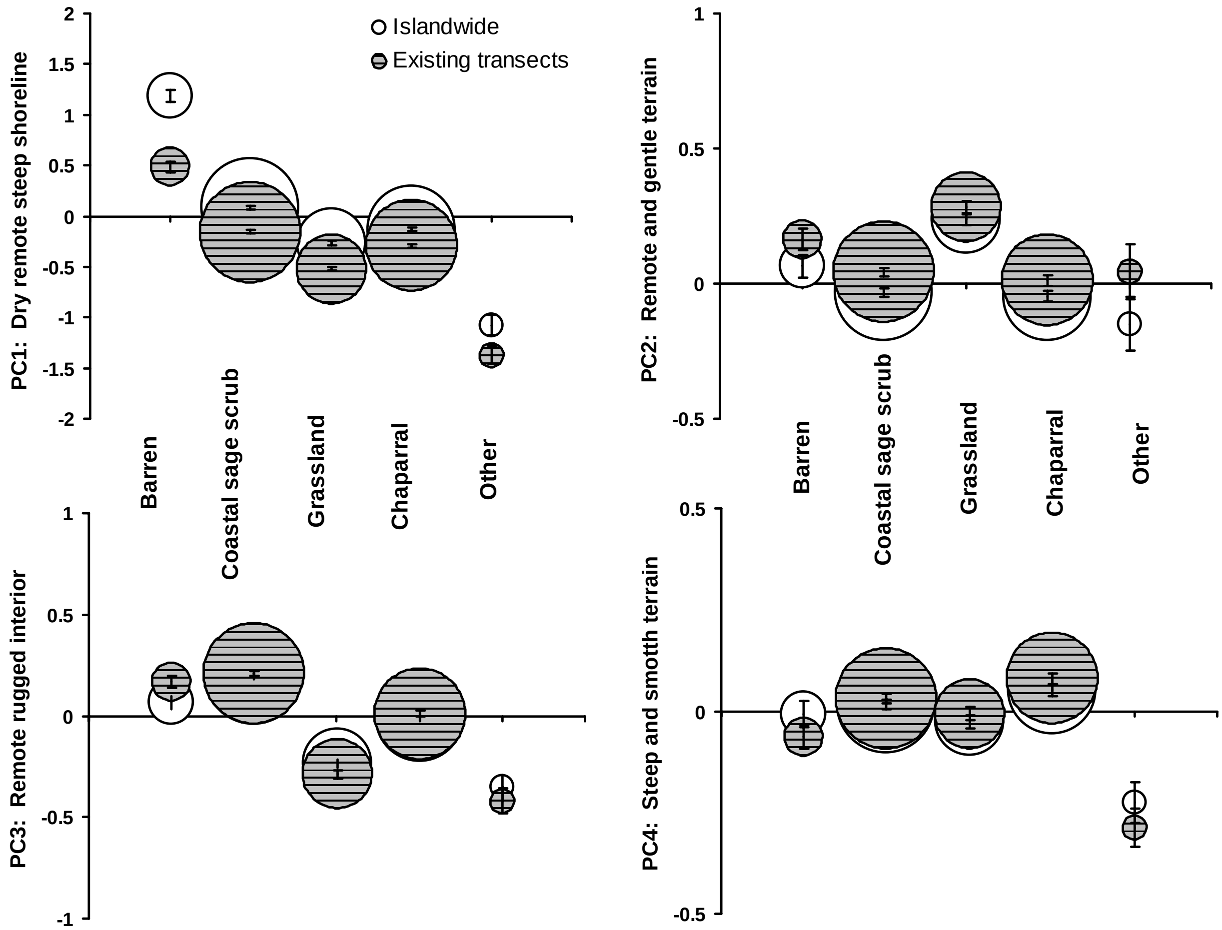

Figure H-2. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped by existing transects relative to the entire East End of Santa Catalina Island by vegetation type for PC1-4. Marker size is weighted by proportional coverage of each vegetation type.

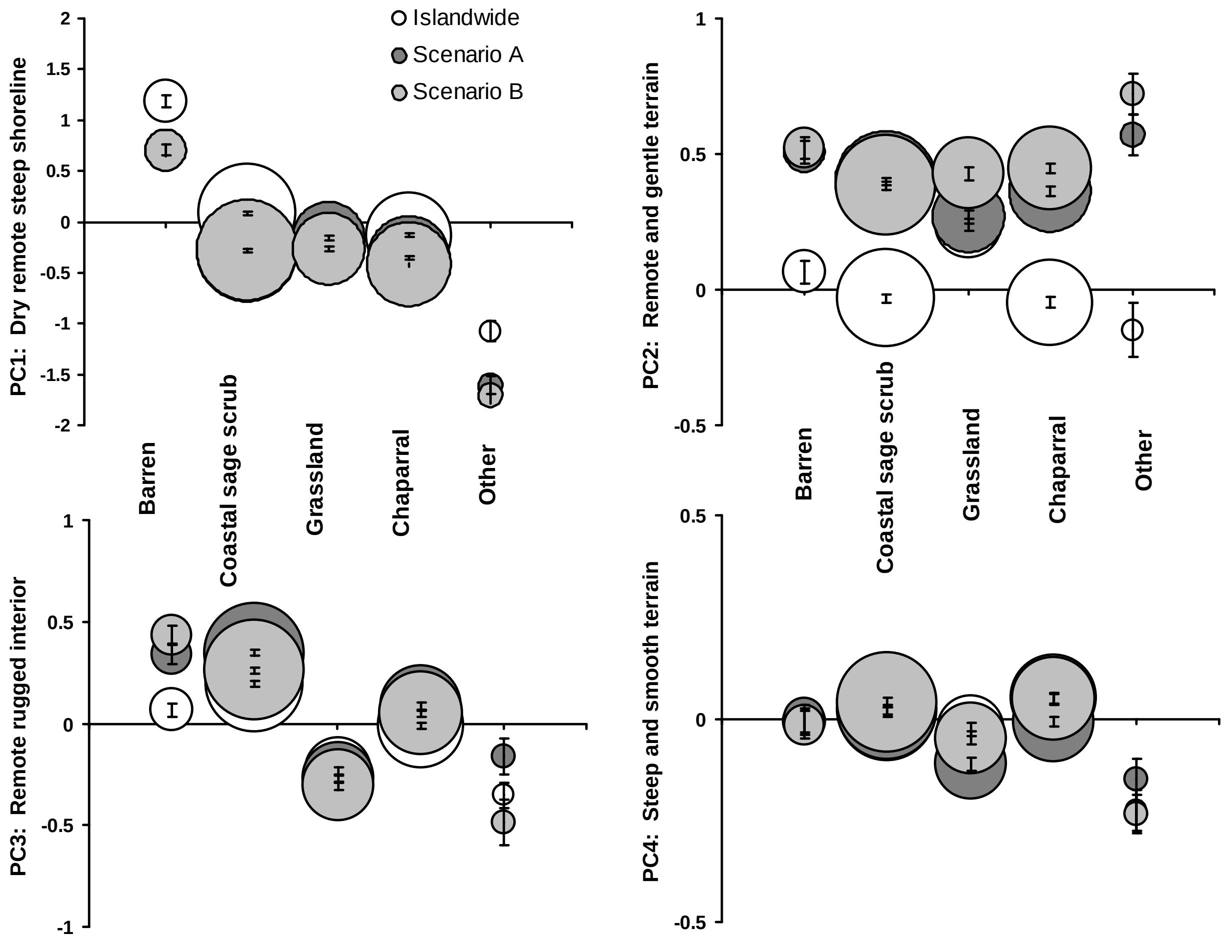

Figure H-3. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenarios A and B relative to the entire East End of Santa Catalina Island by vegetation type for PC1-4. Marker size is weighted by proportional coverage of each vegetation type.

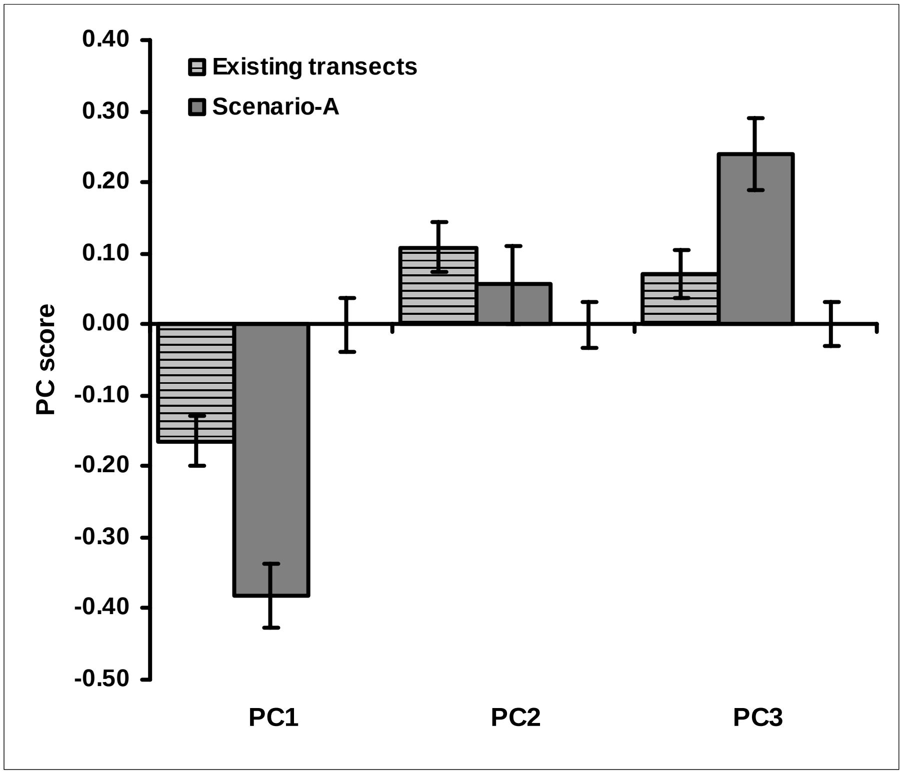

Figure H-4. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped for island foxes and those proposed for trapping under Scenario A. Also shown are confidence intervals for West End (i.e., island-wide) PC scores; the island-wide mean for each PC is 0 because PCA was performed on island data and variables were mean centered and standardized prior to analysis. PC1 represents steep and remote terrain. PC2 is characterizes rugged interior. PC3 represents gentle remote interior.

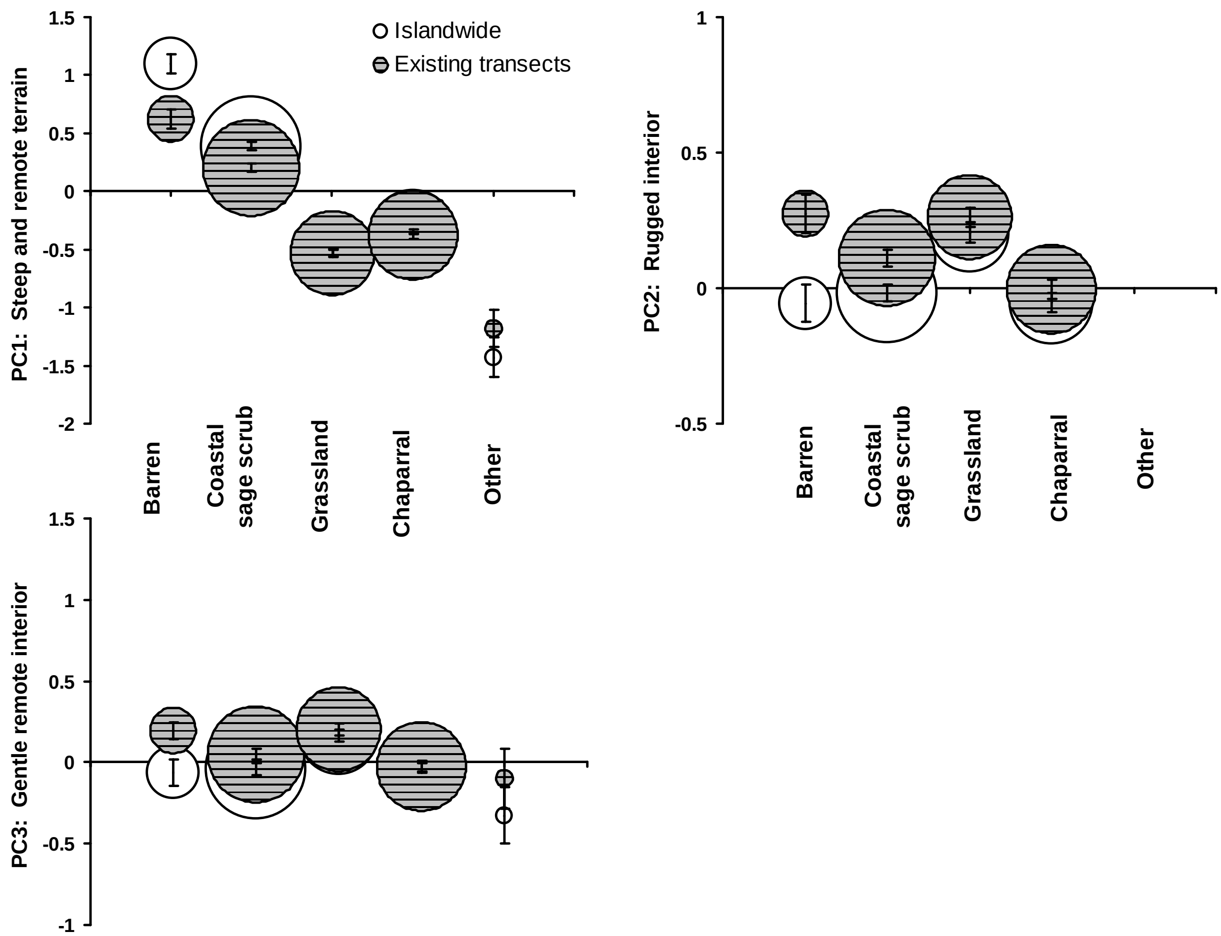

Figure H-5. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped by existing transects relative to the entire West End of Santa Catalina Island by vegetation type for PC1-3. Marker size is weighted by proportional coverage of each vegetation type.

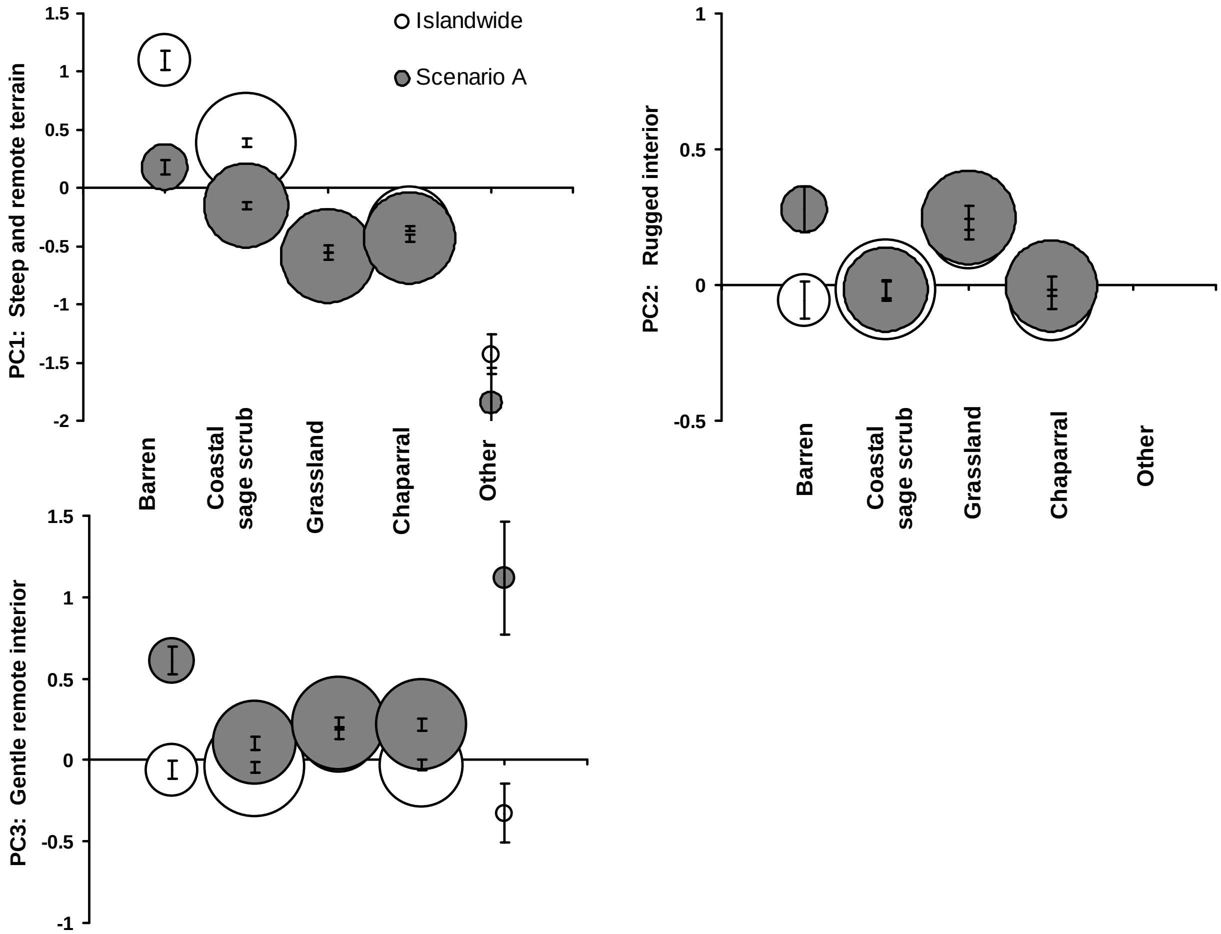

Figure H-6. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenario A relative to the entire West End of Santa Catalina Island by vegetation type for PC1-3. Marker size is weighted by proportional coverage of each vegetation type.

Appendix I

Multivariate Analysis of Habitat Characteristics of Proposed Trapping Scenarios on Santa Rosa Island

Introduction

The monitoring plan in the main body of this report proposes a design for mark-recapture trapping of island foxes on Santa Rosa Island to achieve new monitoring goals for recovering foxes. Under this plan, trapping would consist of a dispersed set of small trapping units (2x6 traps). This appendix uses multivariate statistical methods to evaluate the degree to which proposed trapping locations sample the range of variation on the island for features hypothesized to be important to foxes. The intent of this analysis is to add to the interpretations of the univariate representation analyses by using principal components analysis (PCA) to focus on groups of habitat attributes that tend occur together.

Methods

Six continuous variables were identified as likely to influence fox habitat quality on Santa Rosa Island─slope, ruggedness, distance to roadways, distance to human development, distance to freshwater, and distance to shoreline. These habitat characteristics were extracted from a GIS at randomly located points at a density of ~144 points/km^2), and trapped areas were sampled similarly. Trapped areas were defined as all locations within a 600-m buffer of a trap station. The buffer was added to characterize the entire area likely to be used by foxes entering traps including areas used by foxes living adjacent to grids and captured in perimeter traps. The 600-m buffer is equal to 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. Additional details on methods of habitat characterization for Santa Rosa Island can be found in Appendix D.

To compare the multivariate attributes of trapped areas to those of the entire island, I performed a principal components analysis (SAS Proc Princomp; SAS Institute Inc. 2005) on the island-wide habitat data and compared mean principal component scores for trapped areas to those of island-wide areas overall and by vegetation type. The latter analysis was performed to assess whether the representativeness of trapped areas was influenced by sampling targeted at certain vegetation types that might have biased habitat characteristics. Variables were mean-centered and standardized prior to conducting the PCA (i.e., PCA used the correlation matrix). To allow a visual assessment of the habitat sampled by the trapped areas, I plotted the mean PC scores for both trapped and island-wide areas. I focus on detecting and describing the major differences in the attributes of trapped areas compared to the islands as a whole as evidenced by separation of 95% confidence intervals on the mean PC scores (while recognizing that separation of confidence intervals is a conservative metric for assessing difference (Schenker and Gentleman 2001). Habitat variables were transformed as necessary to achieve approximately normal distributions to improve the normality of PC scores, which is assumed when using PC scores for hypothesis tests.

PCA identifies patterns within multivariate data, eliminates correlation among data, and reduces the dimensionality of multivariate data to simplify analyses. PCA can add to univariate assessments of representation by focusing on groups of habitat attributes that tend occur together, such as steep rugged shoreline, thereby refining the types of areas that are under or overrepresented. See Figure J-1 in Appendix J for an example of how PCA classifies multivariate habitat types.

Results and discussion

PCA interpretations. Four principal components accounts for 85% of the variation on the island (Table I-1).

Table I-1. Eigenvalues of the correlation matrix for PCA on habitat attributes on Santa Rosa Island.

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	2.33	0.39	0.388
2	1.13	0.19	0.576
3	0.91	0.15	0.727
4	0.73	0.12	0.848
5	0.51	0.08	0.933
6	0.4	0.07	1.000

Nearly 40% of the variation in the habitat attributes on Santa Rosa Island is accounted for by PC1, which contained positive loadings from steep and rugged interior areas that are close to roads and development (Table I-2). PC2 accounts for steep, rugged, and remote terrain. PC3 represents steep terrain far from drainages and is referred to as “Steep and dry.” Finally, PC4 represents lands that are far from shoreline, drainages, and development and is referred to as “Dry remote interior.”

Table I-2. Eigenvectors for PCA on habitat attributes on Santa Rosa Island.

	Principal Component			
	1	**2**	**3**	**4**
	Steep rugged interior near roads and development	**Steep and rugged far from roads and development**	**Steep shoreline far from freshwater**	**Remote interior far from freshwater**
Slope[1]	0.39	0.45	0.48	0.00
Ruggedness[2]	0.45	0.43	0.18	0.00
Distance to…				
Paved roads[2]	-0.43	0.58	0.04	0.00
Development[1]	-0.44	0.44	-0.27	0.38
Shoreline[2]	0.42	-0.03	-0.35	0.77
Freshwater[1]	-0.31	-0.28	0.73	0.51

[1] Square-root transformed [2] Cube-root transformed

Representation analysis using PCA

Overall. Both proposed scenarios under-represent PC1 and PC2 (Figure I-1). Thus, steep terrain is under-sampled, regardless of proximity to roads and development. Steep terrain far from drainages appears better sampled (i.e., PC3), suggesting that avoidance of canyons may have contributed to this pattern. Bias away from very steep terrain is unsurprising given that selection criteria attempted to excessive slopes. Finally, inland areas far from drainages and development also modestly under-sampled PC4 (Figure I-1). Both proposed scenarios appear to perform similarly in terms of multivariate representation, although Scenario B samples steep rugged remote terrain somewhat better. The enhanced overall representativeness of Scenario B is achieved by removing trapping units in areas with low slope and close to development rather than by increased sampling of steep rugged remote terrain. Thus, the added trapping grids in Scenario A do not increase the representativeness of the sampling effort.

By vegetation type. Trap locations within the dominant vegetation types, grassland and coastal sage scrub, consistently under-sample PC1, PC2, and PC3 mirroring the overall island-wide patterns (Figure I-2). Thus, trap locations within each vegetation type sample atypical locations with respect to key habitat attributes, favoring locations with gentler terrain closer to shoreline.

Conclusions

Steep terrain on Santa Rosa Island is under-sampled by both proposed trapping scenarios. This bias towards level terrain occurs regardless of proximity to development and roads. Steep terrain far from drainages, however, appears better sampled (i.e., PC3), suggesting that avoidance of canyons may have contributed to this pattern. Unlike many other islands, steep shoreline areas are not underrepresented by either proposed trapping scenario on Santa Rosa Island. Both proposed scenarios appear to perform similarly in terms of multivariate representation, although Scenario B samples steep rugged remote terrain somewhat better. Thus, the additional trapping grids in Scenario A do not increase the multivariate representativeness of this sampling design. 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. Density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to assure that these biases do not bias monitoring program results.

Literature Cited

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Schenker, N., and J.F. Gentleman. 2001. On judging the significance of differences by examining the overlap between confidence intervals. The American Statistician **55**:182-186.

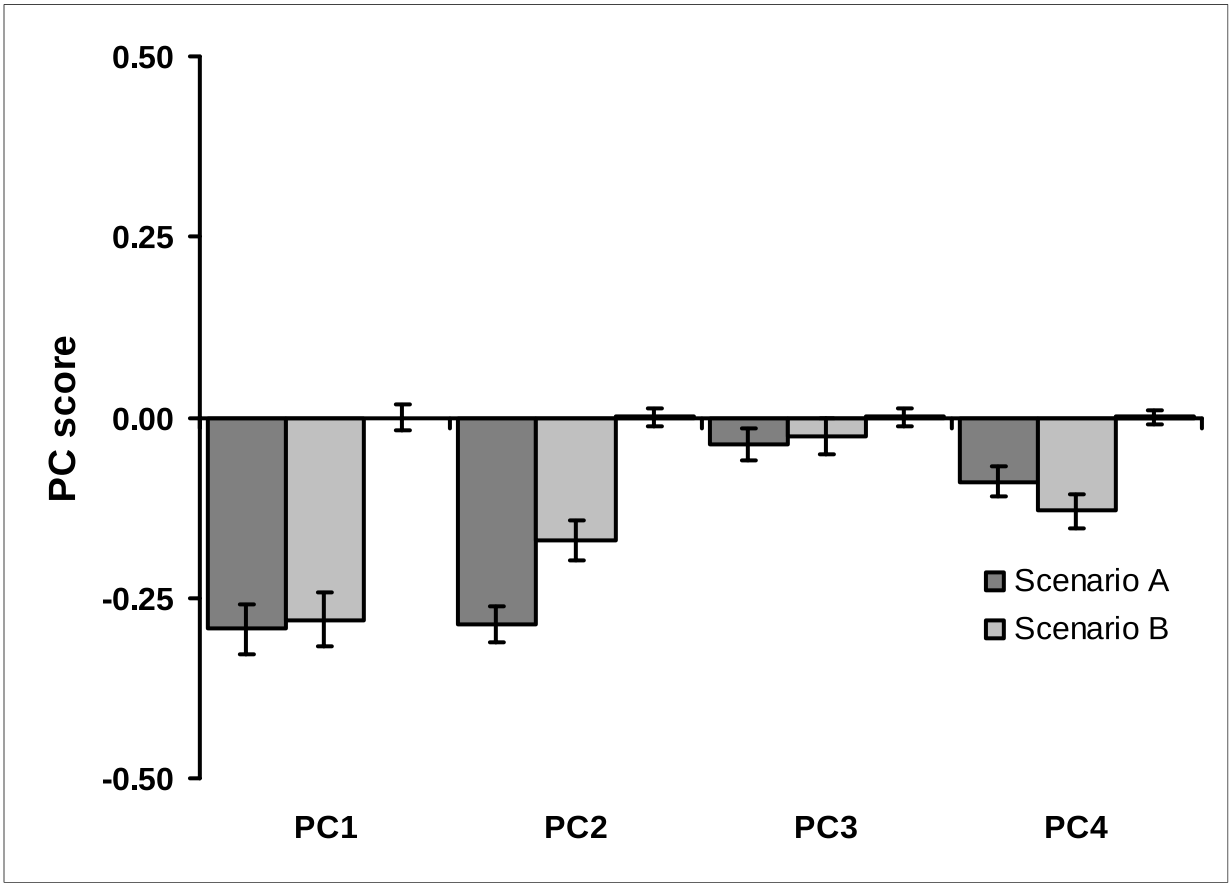

Figure I-1. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenarios A and B relative to the entire island. Also shown are confidence intervals for island-wide PC scores; the island-wide mean for each PC is 0 because PCA was performed on island data and variables were mean centered and standardized prior to analysis. PC1 is steep, rugged interior near roads and development. PC2 is steep and rugged far from roads and development. PC3 is steep shoreline far from freshwater. PC4 is remote interior far from freshwater.

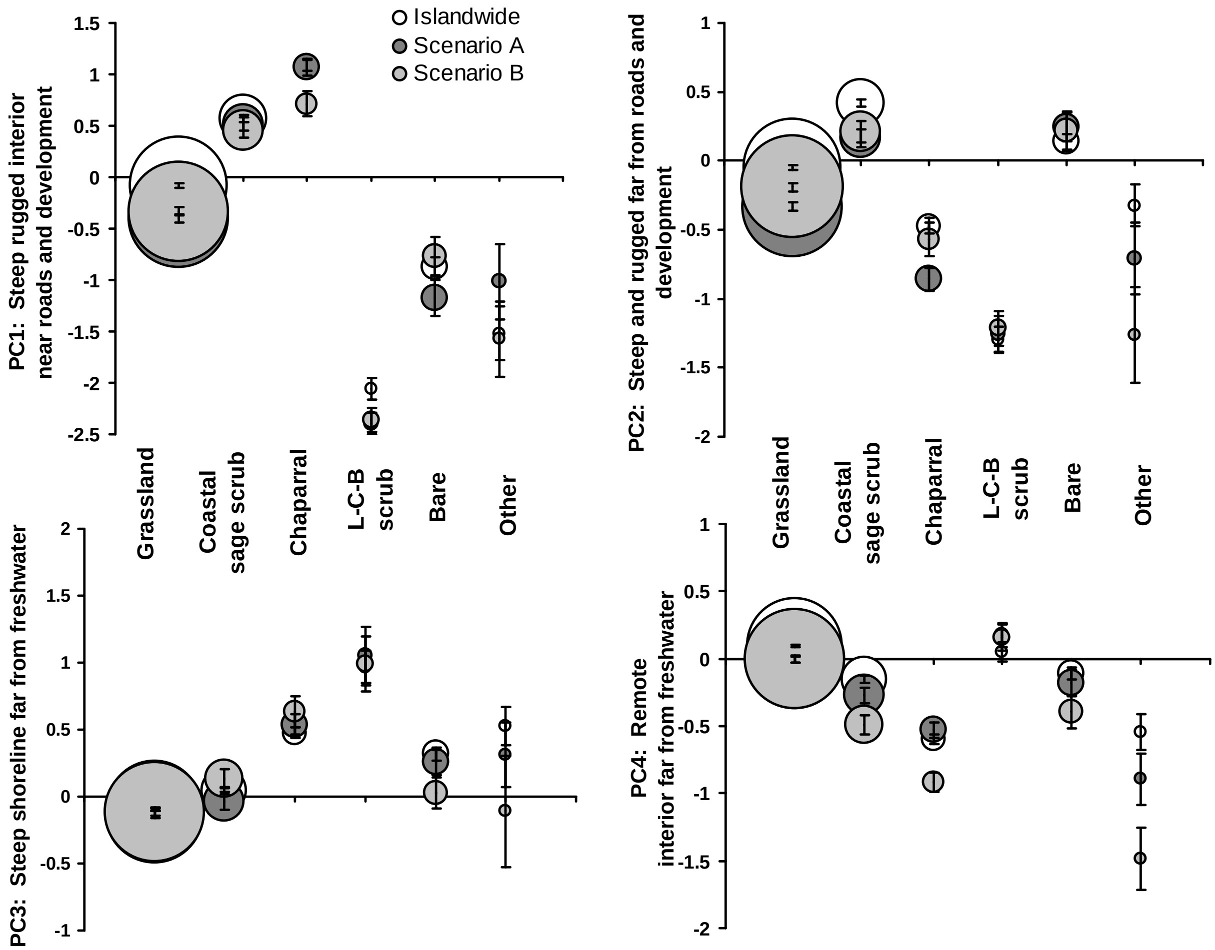

Figure I-2. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenarios A and B relative to the entire island by vegetation type for PC1─PC4. Marker size is weighted by proportional coverage of each vegetation type. L-C-B scrub is Lupine/Caliche/Baccharis Scrub.

Appendix J

Multivariate Analysis of Habitat Characteristics of Existing and Proposed Trapping Scenarios on Santa Cruz Island

Introduction

The monitoring plan in the main body of this report proposes a new design for mark-recapture trapping of island foxes on Santa Cruz Island to increase the efficiency and robustness of monitoring efforts and to achieve new monitoring goals. Under this plan, trapping would consist of a dispersed set of small trapping units (2x6 traps). Historically, island foxes have been trapped using mark-recapture trapping methods with traps arrayed in single line transects throughout the island. This appendix uses multivariate statistical methods to evaluate the degree to which current and proposed trapping locations sample the range of variation on the island for features hypothesized to be important to foxes. The intent of this analysis is to add to the interpretations of the univariate representation analyses by using principal components analysis (PCA) to focus on groups of habitat attributes that tend occur together.

Methods

Five continuous variables were identified as likely to influence fox habitat quality on Santa Cruz Island─slope, ruggedness, distance to roadways, distance to human development, and distance to shoreline. These habitat characteristics were extracted from a GIS at randomly located points at a density of ~144 points/km^2), and trapped areas (existing and proposed) were sampled similarly. Trapped areas were defined as all locations within a 600-m buffer of a trap station. The buffer was added to characterize the entire area likely to be used by foxes entering traps including areas used by foxes living adjacent to grids and captured in perimeter traps. The 600-m buffer is equal to 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. Additional details on methods of habitat characterization for Santa Cruz Island can be found in Appendix E.

To compare the multivariate attributes of trapped areas to those of the entire island, I performed a principal components analysis (SAS Proc Princomp; SAS Institute Inc. 2005) on the island-wide habitat data and compared mean principal component scores for trapped areas to those of island-wide areas overall and by vegetation type. The latter analysis was performed to assess whether the representativeness of trapped areas was influenced by sampling targeted at certain vegetation types that might have biased habitat characteristics. Variables were mean-centered and standardized prior to conducting the PCA (i.e., PCA used the correlation matrix). To allow a visual assessment of the habitat sampled by the trapped areas, I plotted the mean PC scores for both trapped and island-wide areas. I focus on detecting and describing the major differences in the attributes of trapped areas compared to the islands as a whole as evidenced by separation of 95% confidence intervals on the mean PC scores (while recognizing that separation of confidence intervals is a conservative metric for assessing difference (Schenker and Gentleman 2001). Habitat variables were transformed as necessary to achieve approximately normal distributions to improve the normality of PC scores, which is assumed when using PC scores for hypothesis tests.

PCA identifies patterns within multivariate data, eliminates correlation among data, and reduces the dimensionality of multivariate data to simplify analyses. PCA can add to univariate assessments of representation by focusing on groups of habitat attributes that tend occur together, such as steep rugged shoreline, thereby refining the types of areas that are under or over-represented.

Results and Discussion

PCA interpretations. The first principal component accounts for 36% of the variation in habitat variables and three PCs describe nearly 80% of the overall variation on the island (Table J-1).

Table J-1. Eigenvalues of the correlation matrix for PCA on habitat attributes on Santa Cruz Island

Principal component	Eigenvalue	Proportion of variance	Cumulative variance
1	1.79	0.36	0.358
2	1.19	0.24	0.596
3	0.93	0.19	0.782
4	0.83	0.17	0.948
5	0.26	0.05	1

PC1 represents areas that are far from roads and development but close to shoreline (Table J-2); referred to here as “Unroaded remote shoreline.” PC2 accounts for steep and rugged terrain far from development and shoreline, label here as “Remote steep and rugged interior.” Finally, PC3 is heavily influenced by rugged areas with low slopes, labeled “Flat rugged terrain.”

Table J-2. Eigenvectors for PCA on habitat attributes on Santa Cruz Island

	Principal Component		
	1	**2**	**3**
	Unroaded remote shoreline	**Remote steep and rugged interior**	**Flat rugged terrain**
Slope	0.12	0.52	-0.76
Ruggedness[1]	-0.11	0.58	0.62
Distance to…			
Roads[2]	0.69	0.00	0.14
Development[3]	0.51	0.43	0.11
Shoreline[3]	-0.48	0.45	-0.02

[1] ln transformed [2] Cube-root transformed [3] Square-root transformed

Representation analysis using PCA

Overall. Existing transect trapping on Santa Cruz Island has underrepresented unroaded remote shoreline areas, such as those found on the north and west ends and the south side of the island (Figures J-1 and J-2). Existing transects have also under-sampled remote rough interior areas but well represented rugged terrain on flatter ground (Figures J-1 and J-2). Proposed Scenario A also under-samples unroaded remote shoreline, but achieves substantially better coverage of these areas than existing transects, while Scenario B is unbiased with respect to unroaded remote shoreline. Scenarios A and B perform similarly to existing transects in under-sampling remote steep and rugged interior areas. In addition, both over-sample flat rugged terrain. The observed biases are unsurprising and seem to reflect selection criteria, in which trapping units are linked to roadways and very steep areas are avoided to ensure the feasibility of sampling.

By vegetation type. Existing and proposed trapping areas appear to sample vegetation types in a manner roughly proportional to their occurrence. Under-sampling of unroaded remote shoreline occurs systematically in all vegetation types for existing transects and proposed Scenario A (Figures J-3 and J-4). Scenario B, in contrast, samples remote shoreline in a representative manner but over-samples this feature within herbaceous vegetation and under-samples it within all minor vegetation types. For existing and proposed trapping areas, remote rough interior is under-sampled in most vegetation types, except for herbaceous vegetation, where habitat attributes reflect those of the vegetation type as a whole. Finally, flat rugged terrain is well represented within major habitat types by existing trapping locations, but generally over-sampled across habitat types by proposed scenarios.

Conclusions

Existing transects and proposed Scenario A under-represent unroaded remote shoreline characteristic of areas on the north, west, and the south sides of the island, while Scenario B represents this feature consistent with its overall presence on the island. Existing transects and both proposed scenarios under-sample remote steep and rugged interior areas to a similar degree. Proposed scenarios over-sample rugged terrain on flatter ground. Overall, Scenario B appears to represent the habitat characteristics of the island best, despite fewer trapping units overall. This efficiency is achieved because most of the additional trapping units comprising Scenario A occur in areas that are closer to roads and development, which tend to be over-sampled. 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. Density and demographic rates in disproportionately sampled habitat types should be compared to overall island-wide patterns to assure that these biases do not bias monitoring program results.

Literature Cited

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Schenker, N., and J.F. Gentleman. 2001. On judging the significance of differences by examining the overlap between confidence intervals. The American Statistician **55**:182-186.

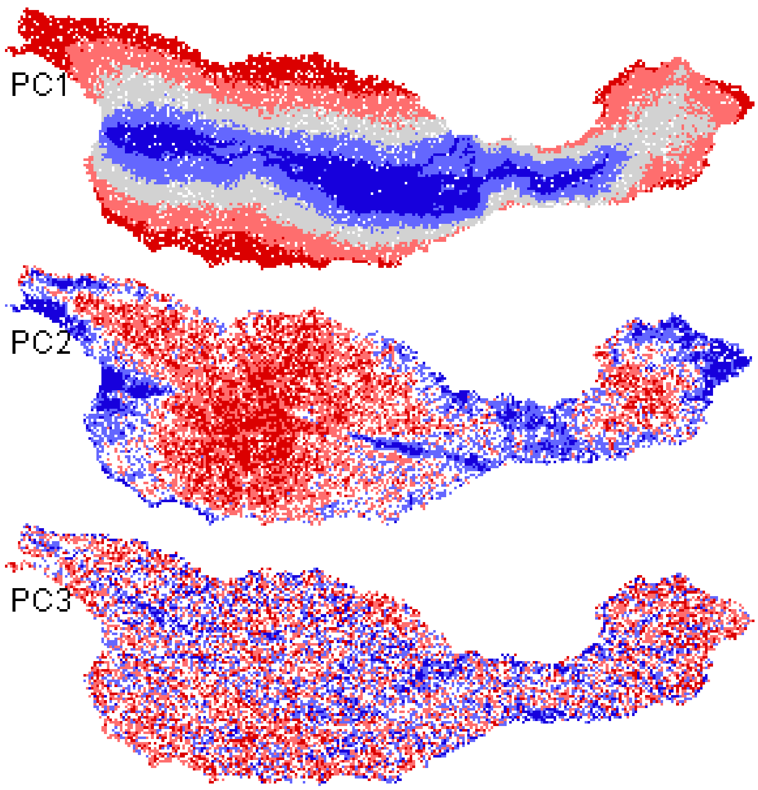

Figure J-1. Example of how PCA differentiates multivariate habitat types. Red indicates high values for a particular PC while blue indicates low values. PC1 is remote shoreline areas, PC2 is remote, steep, and rugged interior lands, and PC3 is flat rugged terrain

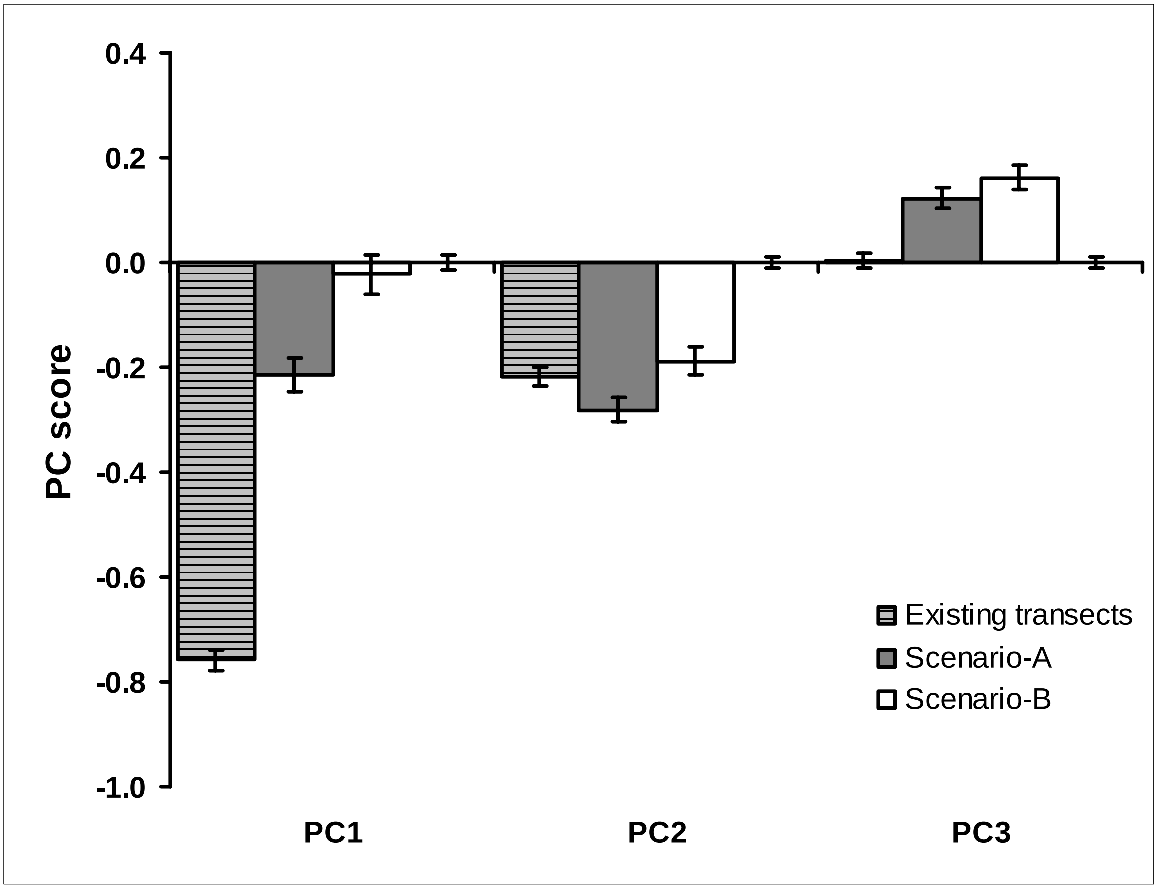

Figure J-2. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped for island foxes and those proposed for trapping under Scenarios A and B. Also shown are confidence intervals for island-wide PC scores; the island-wide mean for each PC is 0 because PCA was performed on island data and variables were mean centered and standardized prior to analysis. PC1 is remote shoreline areas, PC2 is remote, steep, and rugged interior lands, and PC3 is flat rugged terrain

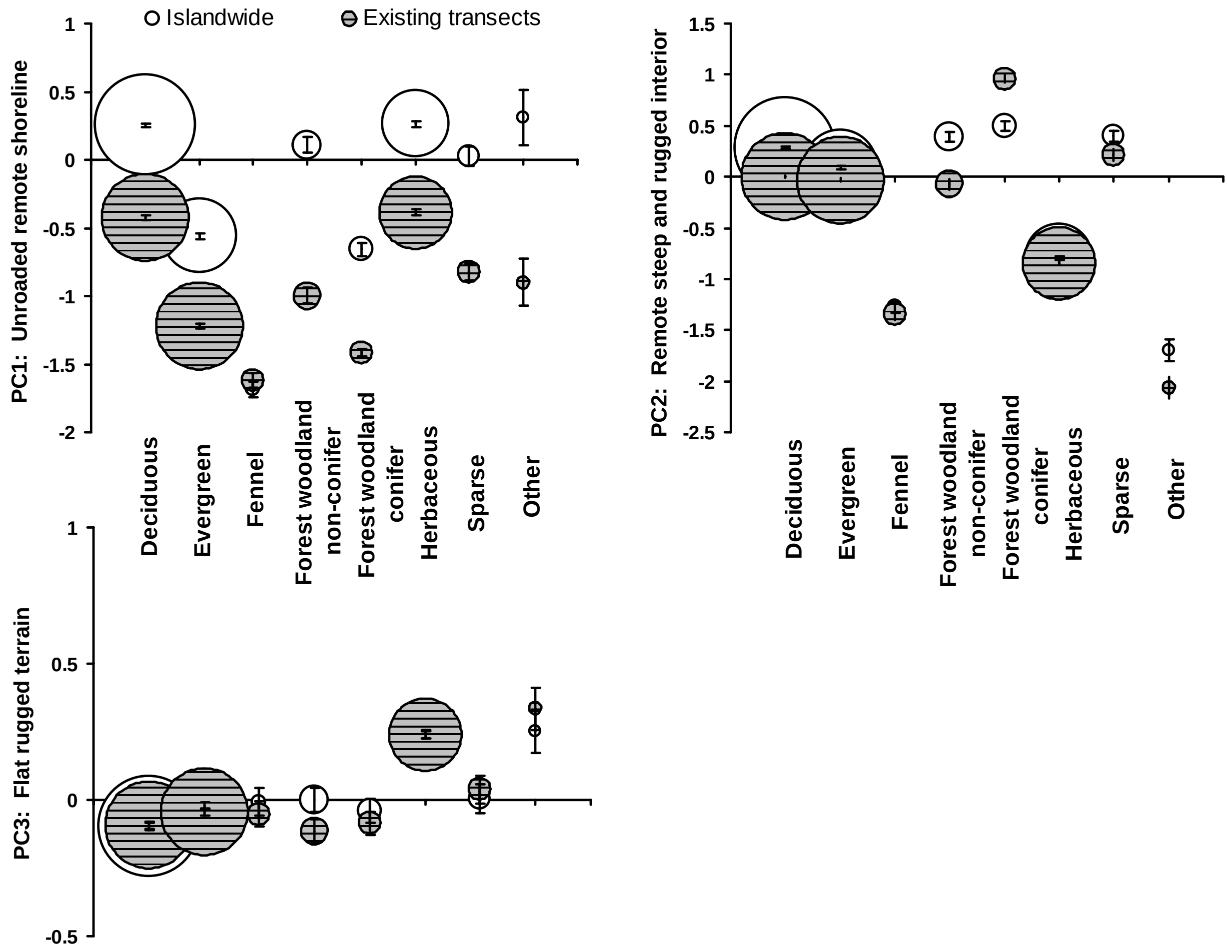

Figure J-3. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas currently trapped by existing transects relative to the entire island by vegetation type for PC1, PC2, and PC3. Marker size is weighted by proportional coverage of each vegetation type.

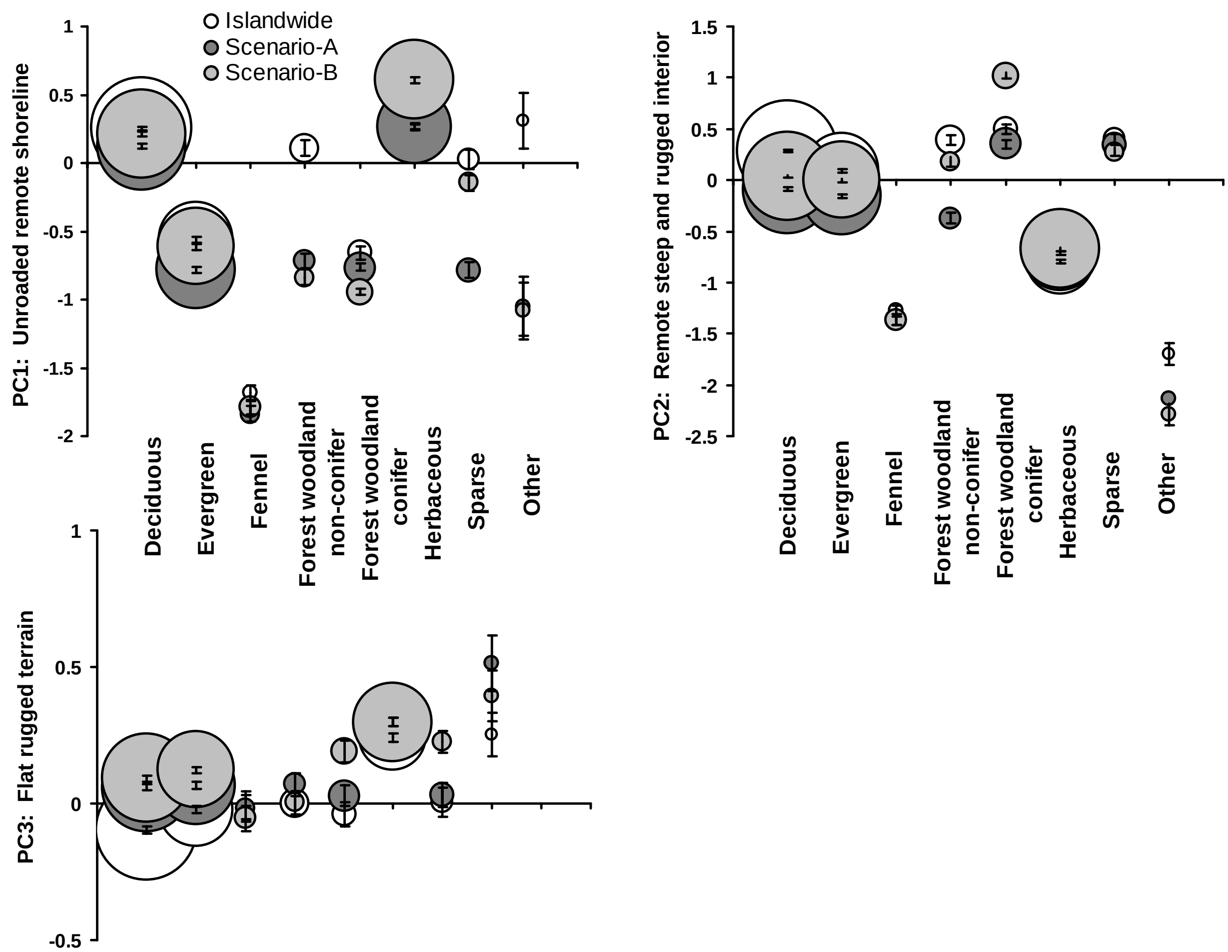

Figure J-4. Comparison of mean (± 95% confidence intervals) PC scores for habitat attributes in areas proposed for trapping under Scenarios A and B relative to the entire island by vegetation type for PC1, PC2, and PC3. Marker size is weighted by proportional coverage of each vegetation type.

APPENDICES K–M

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Note: These appendices summarize exploratory analyses conducted in support of recommendations in the main framework report and are not intended to be stand-alone documents.

K Monitoring Island Fox Populations by Trapping and Spatially Explicit Capture-Recapture: Options for San Miguel Island

L Simulations of Trapping Regimes for Island Foxes on San Nicolas Island Using an Island-wide Grid, and with Variations on the Present Grid Trapping

M Monitoring Island Fox Populations by Trapping and Spatially Explicit Capture–Recapture: Options for Santa Catalina, Santa Rosa, and Santa Cruz

Appendix K

Monitoring Island Fox Populations by Trapping and Spatially Explicit Capture-Recapture: Options for San Miguel Island

The aim is to evaluate three trapping options for San Miguel, two of them based on the present trap protocol, and the other a local implementation of the trapping unit design addressed in the main report. Initially, options were limited to a maximum of 288 trap nights per year, but it became clear that this is inadequate. After feedback from CBI, further options were added with 5 grids of 18, 24, 30 or 36 traps, trapped over 6 nights.

Simulations

Various grid shapes and sizes for 4-6 nights, evaluated in terms of expected number of recaptures.

A single file was used for each layout, but the grids were spaced far apart (4 km) and detection was truncated at 2 km, so the trial represents independent trapping of grids, consistent with sequential trapping as occurs in reality. Note that the large spacing between grids was merely a convenient way of conducting the simulations to achieve independence.

In Addendum A, CBI had requested an evaluation of the present design in which closely spaced grids are trapped sequentially (Scenario 1; Figure K-1). On reflection, it is not clear how to analyse such data, and they cannot easily be simulated. In essence there is negligible difference between Scenarios 1 and 2 proposed in Addendum A. I simulated Scenario 2 in which grids are treated as independent, and are far enough apart that between-grid movements are rare.

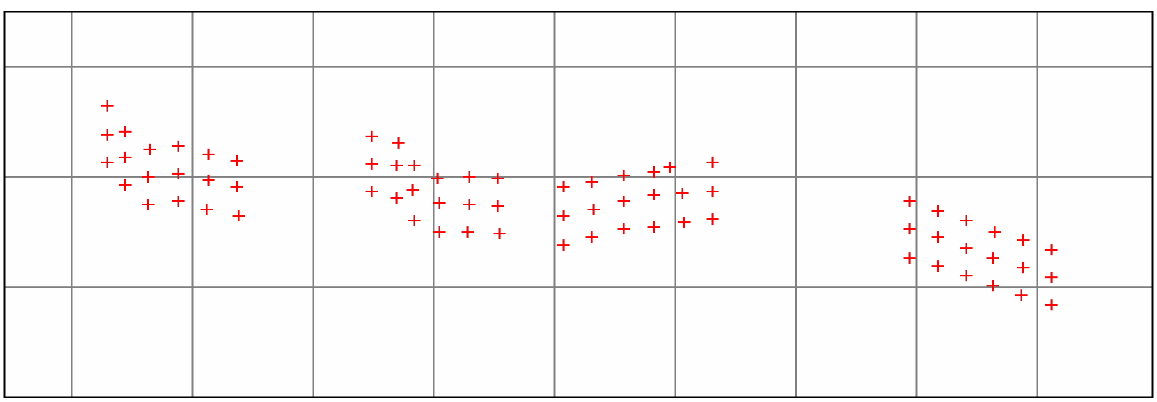


Figure K-1. San Miguel's present grids. 72 traps in 4 grids. Trap spacing nominally 200 m, but, by my calculation, actual mean distance to nearest trap is 227 m. 1-km squares.

Parameter values from trapping on San Miguel (±1SE)

Historical trapping data on San Miguel span both high and low densities.

1. T. Coonan 2006 sent directly to M. Efford. Asynchronous data analysed as synchronous. $D = 1.91 \pm 0.44$, $g0 = 0.092 \pm 0.023$, $\sigma = 573 \pm 77$ [Halfnormal detection]. The large estimate of σ reflects large between-grid 'movements' in the data; it is difficult to know whether these reflect large short-term (4-day) home ranges or dispersal or a few itinerant foxes. We choose not to rely on this estimate of the detection function.
2. V. Bakker's analysis of 6-years of data from the 14x7 SMWC grid. Density was low (<4 / km^2) in the second half of the study, when detectability was also low (average for years 4–6: $g_0 = 0.06$, $\sigma = 279$).
3. V. Bakker's analysis of 3 years of data from the 6x8 DLB grid spanning 1 high density year and 2 lower density years. The pooled estimates were $g_0 = 0.08$, $\sigma = 206$.

Estimates from other islands commonly give larger estimates of g_0 & σ. For San Miguel simulations I have used the new benchmark detection parameter values as a 'best case' ($g_0 = 0.08$, $\sigma = 300$) and two more pessimistic scenarios.

Table K-1. Detection scenarios for San Miguel. Halfnormal detection function.

SM scenario	***D***	***g_0***	**σ**	**Note**
1	2	0.08	300	Best case
2	2	0.06	300	
3	2	0.06	200	Worst case

Table K-2. Summary of layouts.

	Number	**Layout**	**Spacing**	**No. of nights**	**Trap nights**	**Note**
1	4	3 x 6	200	4	288	Similar to status quo
2	4	3 x 6	250	4	288	Increased spacing
3	6	2 x 6	200	4	288	
4	6	2 x 6	200	6	432	
5	8	2 x 6	200	6	576	
6	5	3 x 6	200	6	540	
7	5	4 x 6	200	6	720	
8	5	5 x 6	200	6	900	
9	5	6 x 6	200	6	1080	

Results and Interpretation

None of the layouts with 288 trap nights per year produces enough recaptures for capture-recapture analysis (Table K-3). In part this is because the second and third detection scenarios are quite pessimistic, but the first one is quite plausible. Even with double the number of trap nights, there are not enough recaptures (target of approximately 33 recaptures for CV ≤20%). The target is reached when trapping is extended to 5 grids of at least 30 traps each and trapping is conducted for 6 nights.

Table K-3. Simulated average numbers of individuals and numbers of within-grid recaptures for grid layouts as in Table K-2. Detection scenarios 1–3 as in Table K-1; numbers incorporate the layout numbers from Table K-2 after the decimal place.

Scenario	No.of grids	Layout	Nights	Trap-nights	Animals	Recaptures	Recaptures per trap-night
1.1	4	3 x 6	4	288	13.8	7.5	.026
1.2	4	3 x 6	4	288	15.1	6.8	.024
1.3	6	2 x 6	4	288	15.8	6.4	.022
1.4	6	2 x 6	6	432	20.1	13.4	.031
1.5	8	2 x 6	6	576	26.5	17.8	.031
1.6	5	3 x 6	6	540	21.0	18.5	.034
1.7	5	4 x 6	6	720	25.0	26.1	.036
1.8	5	5 x 6	6	900	29.2	33.6	.037
1.9	5	6 x 6	6	1080	33.0	41.2	.038
2.1	4	3 x 6	4	288	11.7	4.9	.017
2.2	4	3 x 6	4	288	13.0	4.6	.016
2.3	6	2 x 6	4	288	13.2	4.1	.014
2.4	6	2 x 6	6	432	17.2	9.0	.021
2.5	8	2 x 6	6	576	22.9	11.7	.020
2.6	5	3 x 6	6	540	18.7	13.0	.024
2.7	5	4 x 6	6	720	22.3	18.7	.026
2.8	5	5 x 6	6	900	26.0	23.9	.027
2.9	5	6 x 6	6	1080	29.7	29.6	.027
3.1	4	3 x 6	4	288	6.0	1.8	.006
3.2	4	3 x 6	4	288	6.6	1.5	.005
3.3	6	2 x 6	4	288	6.6	1.5	.005
3.4	6	2 x 6	6	432	8.8	3.4	.008
3.5	8	2 x 6	6	576	11.6	4.4	.008
3.6	5	3 x 6	6	540	10.0	4.9	.009
3.7	5	4 x 6	6	720	12.6	7.1	.010
3.8	5	5 x 6	6	900	15.1	9.1	.010
3.9	5	6 x 6	6	1080	17.5	11.2	.010

Addendum A

Simulations of trapping regimes for island foxes on San Miguel using an island-wide grid

The aim of these simulations was to evaluate island-wide trapping options for a small island such as San Miguel. Previous simulations had shown island-wide trapping was impractical for Santa Cruz (about 251 km^2). Island-wide trapping is attractive because it avoids the need to extrapolate from sampled areas to the whole, which entails estimation of density at the scale of each grid or transect. Its main drawbacks are

- the need to shift traps to randomize access by foxes to traps: repeated trapping at fixed sites samples the local population, not the whole.
- the large distances that must be traversed off-road.

Simulated trapping grid

A digitized coastline of San Miguel was provided by B. Cohen, TNC.
The island has an area of 38.6 km^2.

The same three scenarios were used for D, g(0), σ as on Santa Cruz.

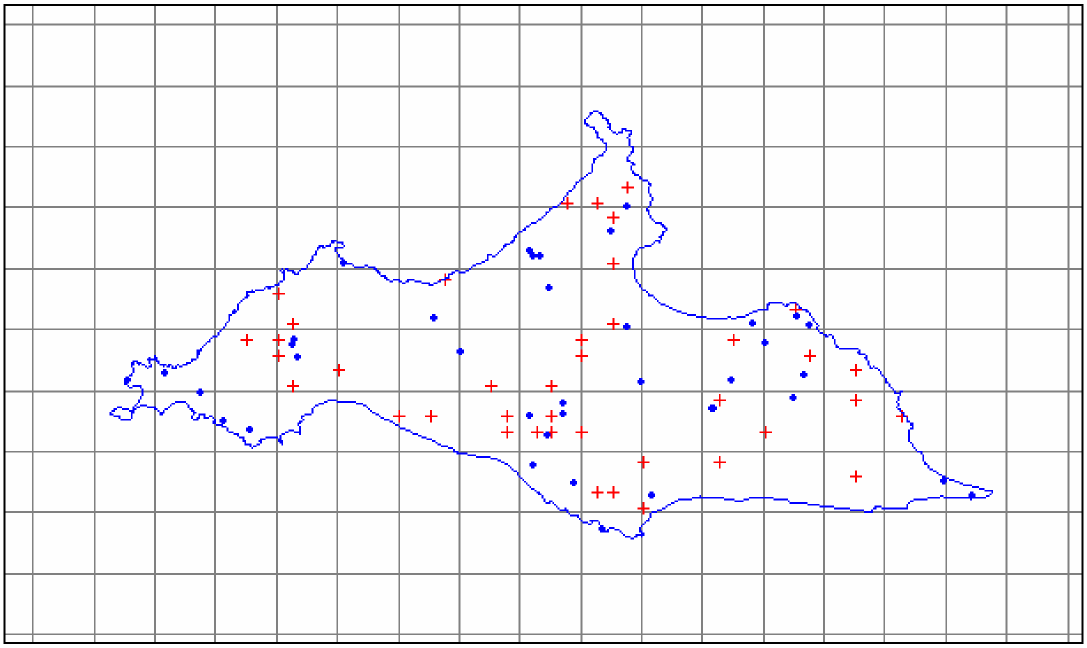
Simulations were grouped in two trials, one with random selection of sites from a 250-m grid, and the other with a fixed trap spacing but randomly shifted origin. The emphasis here is on the second trial as this delivered slightly better precision.

100 replicate simulations were performed for each combination. Detection was assumed to follow a halfnormal function.

San Miguel Trial 1

Daily select a new random subset of these trap sites.
Sampling fraction chosen to give 40 traps.
5 or 15 trapping nights.

Scenario	**D km^{-2}**	**No. of foxes**	**g(0)**	**σ m**	**Grid spacing m**	**Sampling fraction**	**No. of traps**	**Nights**
1.1	1	38.6	0.05	600	250	0.06472	40	5
1.2					250	0.06472	40	15
2.1	4	154.4	0.1	300	250	0.06472	40	5
2.2					250	0.06472	40	15
3.1	4	154.4	0.2	300	250	0.06472	40	5
3.2					250	0.06472	40	15



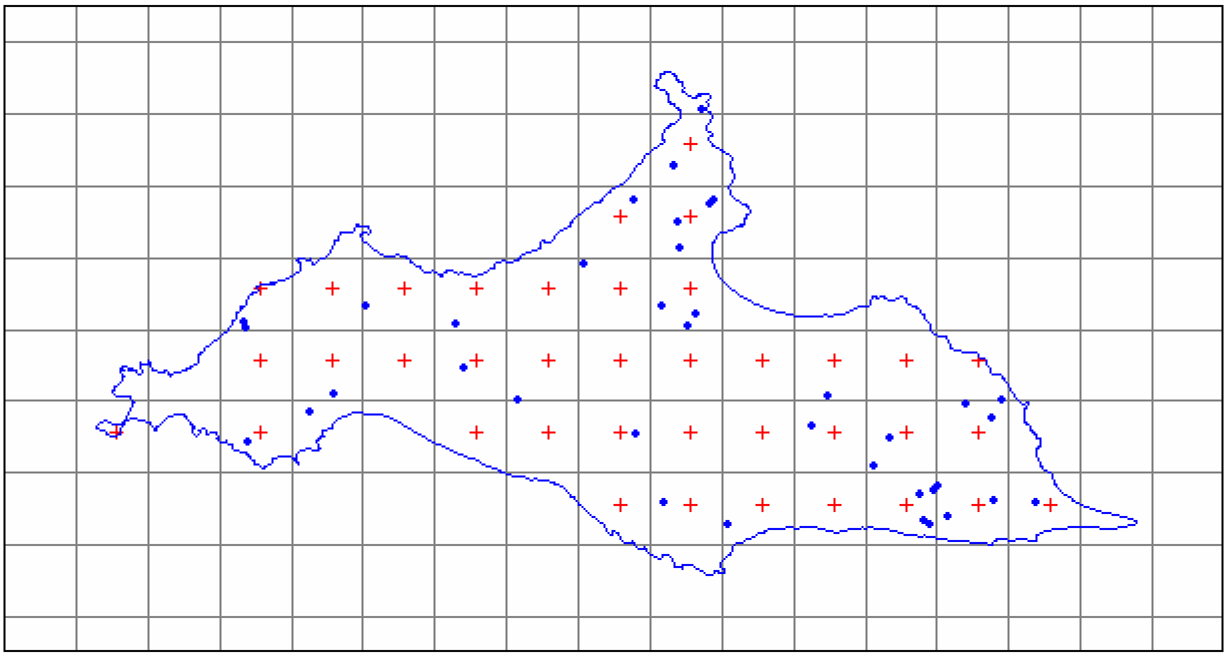
Example: Trial 1, Scenario 1, 40 traps selected at random from 250-m grid (red crosses), ≈38 random foxes (gridlines 1-km spacing).

San Miguel Trial 2

Daily shift entire grid by a random distance in x- and y- directions. 'Jittering' is uniform on the range ± 0.5 × trap spacing.
Trap numbers are approximate because some shifts move grid points onshore or offshore.
5 or 15 trapping nights.

Scenario	**D km^{-2}**	**No. of foxes**	**g(0)**	**σ m**	**Grid spacing m**	**Jitter m**	**No. of traps**	**Nights**
1.1	1	38.6	0.05	600	500	± 250	152	5
1.2					750	± 375	67	5
1.3					1000	± 500	39	5
1.4					500	± 250	152	15
1.5					750	± 375	67	15
1.6					1000	± 500	39	15
2.1	4	154.4	0.1	300	500	± 250	152	5
2.2					750	± 375	67	5
2.3					1000	± 500	39	5
2.4					500	± 250	152	15
2.5					750	± 375	67	15
2.6					1000	± 500	39	15
3.1	4	154.4	0.2	300	500	± 250	152	5

Scenario	D km^{-2}	No. of foxes	g(0)	σ m	Grid spacing m	Jitter m	No. of traps	Nights
3.2					750	± 375	67	5
3.3					1000	± 500	39	5
3.4					500	± 250	152	15
3.5					750	± 375	67	15
3.6					1000	± 500	39	15



Example: Trial 2, Scenario 1.3, 38 traps at 1,000-m spacing (red crosses), ≈38 random foxes (gridlines 1-km spacing)

San Miguel Trial 3

This was a targeted trial to evaluate the effect of progressively increasing the number of trap nights. Settings otherwise followed Trial 2 Scenario 2.3.

Analysis
A null capture-recapture model was fitted because jittered trap placement should have largely eliminated heterogeneity.

Results

Table. San Miguel Trial 1.

Density	g0	σ	NTraps	Spacing	Occasions	Nhat	RelBias%	CVNhat%
1	0.05	600	40	[250]	5	41.4	7.4	52.0
1	0.05	600	40	[250]	15	37.8	-2.1	13.7
4	0.1	300	40	[250]	5	193.9	25.6	57.3
4	0.1	300	40	[250]	15	154.5	0.1	14.8
4	0.2	300	40	[250]	5	155.4	0.7	26.8
4	0.2	300	40	[250]	15	149.4	-3.2	6.9

Table. San Miguel Trial 2.

Density	g0	σ	NTraps	Spacing	Occasions	Nhat	RelBias%	CVNhat%
1	0.05	600	151	500	5	38.8	0.6	7.1
1	0.05	600	69	750	5	38.3	-0.8	21.3
1	0.05	600	39	1000	5	44.9	16.4	44.1
1	0.05	600	151	500	15	37.6	-2.4	0.6
1	0.05	600	69	750	15	37.8	-2.0	4.2
1	0.05	600	39	1000	15	37.5	-3.0	10.2
4	0.1	300	151	500	5	153.3	-0.7	9.7
4	0.1	300	69	750	5	154.8	0.3	24.8
4	0.1	300	39	1000	5	179.9	16.5	50.1
4	0.1	300	151	500	15	154.1	-0.2	1.8
4	0.1	300	69	750	15	153.8	-0.3	6.4
4	0.1	300	39	1000	15	155.6	0.8	13.0
4	0.2	300	151	500	5	153.4	-0.6	4.0
4	0.2	300	69	750	5	157.5	2.0	12.1
4	0.2	300	39	1000	5	171.5	11.1	25.1
4	0.2	300	151	500	15	151.7	-1.7	0.4
4	0.2	300	69	750	15	154.2	-0.1	2.5
4	0.2	300	39	1000	15	155.3	0.6	6.0

Highlighting emphasises the most attractive option in each table.

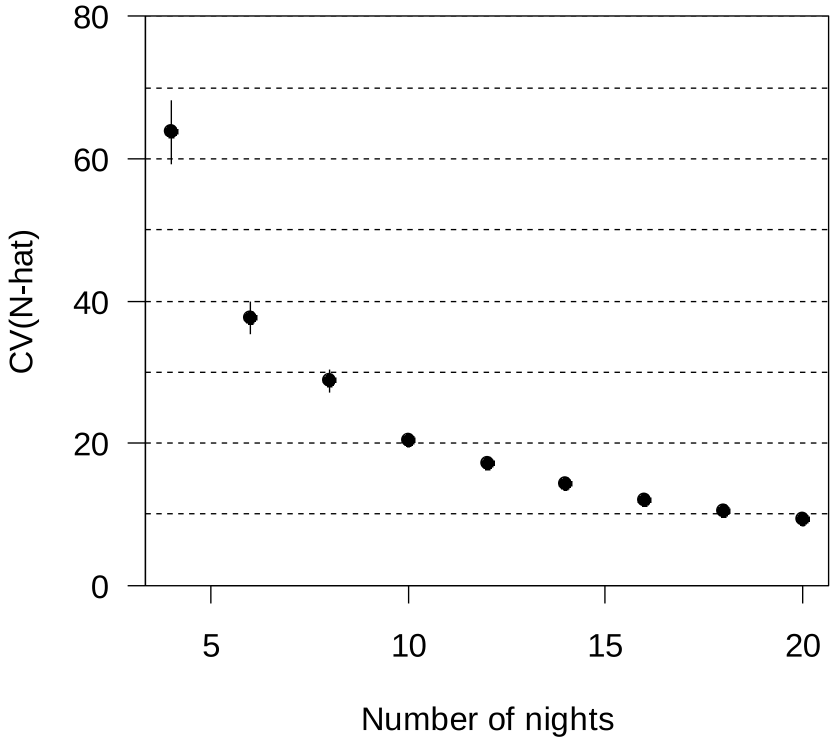


Fig. Precision as a function of increasing number of trapping nights for jittered 1,000-m grid on San Miguel. D = 4.0 / km^2, g(0) = 0.1, σ = 300 m. (Results from Trial 3). Vertical bars are 95% CI for CV(N-hat) across replicates (n = 100).

Interpretation

Bias is a problem here only under conditions that produce unacceptably imprecise estimates, so it is sufficient to evaluate the different regimes in terms of precision.

Very precise estimates may be obtained for some parameter sets with a large jittered grid over 5 nights, but (i) high precision is not guaranteed and (ii) it is probably impractical to 'jitter' such a large grid daily.

Extending trapping over 15 nights produces good results even with as few as 39 traps if these are relocated daily, either to random points on a 250-m grid (Trial 1) or by shifting the entire grid as a unit (Trial 2).

Appendix L

Simulations of Trapping Regimes for Island Foxes on San Nicolas Island Using an Island-wide Grid, and with Variations on the Present Grid Trapping

Trial 1

Simulations

A digitized coastline was provided by B. Cohen, TNC.
San Nicolas has an area of 58.3 km^2.

Three scenarios were used for simulations, two used the new 'standard' detection parameters $g_0 = 0.08$, $\sigma = 300$ m with differing density ($D = 1,4$ / km^2, and the third had high density and low sigma to match the possible current situation on San Nicolas ($D = 9$ / km^2, $g_0 = 0.1$, $\sigma = 200$ m). Detection was assumed to follow a halfnormal function.

Table L-1. Detection scenarios for San Nicolas Island.

SN scenario	***D***	$\boldsymbol{g_0}$	**Σ**
1a	1	0.08	300
2a	4	0.08	300
3	9	0.1	200

For each simulation a grid of traps spaced at 750 m, 1,000 m, or 1,250 m was overlaid on the coastline and uniformly 'jittered' by half the trap spacing each day. Sites falling in the sea were rejected. 200 replicate simulations were performed for each parameter combination.

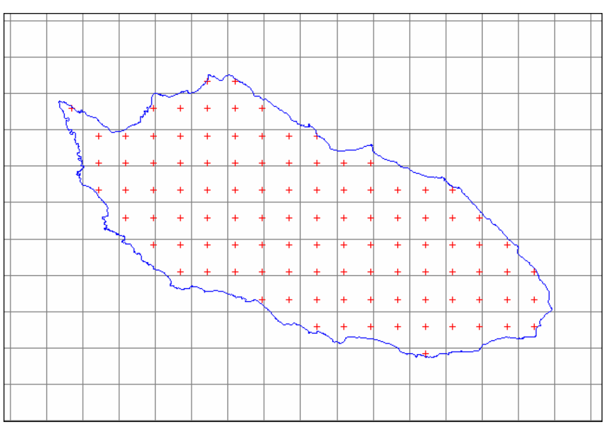


Figure L-1. Example of jittered overlay of traps at 750-m spacing on San Nicolas Island.

A null capture-recapture model (M_0) was fitted to estimate *N* because jittered trap placement should have largely eliminated heterogeneity.

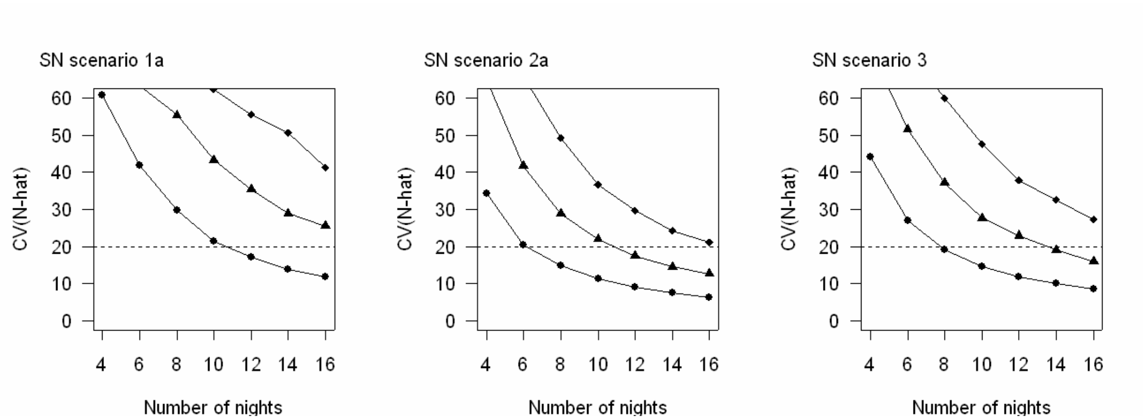


Figure L-2. Precision of estimated population size with jittered island-wide grids for San Nicolas Island. Circles 750-m trap spacing; triangles 1,000 m trap spacing; diamonds 1,250 m trap spacing.

Results and interpretation

Precision is summarised in Figure 2. Data and R code for plotting are in the file 'san nicolas task 2 simulations.spl'.

Adequate precision (CV(*N*-hat) <20%) is achieved only with a large number of traps (Scenario 2a: average 104 traps at 750 m spacing for 6 nights, or average 58 traps at 1,000 m spacing for 11 nights). This partly reflects the larger size of San Nicolas compared to San Miguel.

Bias in *N*-hat was noticeable for large trap spacings when σ was small (the third scenario) (median relative bias +1%, +3%, +16% for spacing 750 m, 1,000 m, 1,250 m) but otherwise median RB(*N*-hat) < 10% (see data file).

Trial 2

Simulations

Various grid shapes and sizes for 4-6 nights, evaluated in terms of expected number of recaptures.

A single file was used for each layout, but the grids were spaced far apart (4 km) and detection was truncated at 2 km, so the trial represents independent trapping of grids, consistent with sequential trapping as occurs in reality. Note that the large grid spacing was *only* a convenient way of conducting the simulations to achieve independence.

Table L-2. Summary of grids. Trap spacing 250 m in each case.

	Number	Layout	No. of nights	Trap nights	Note
1	3	5 x 10	6	900	Similar to status quo
2	4	6 x 8	6	1152	Extra grid
3	4	5 x 10	6	1200	Extra grid
4	5	6 x 6	5	900	Smaller grids
5	10	4 x 6	4	960	Smaller grids
6	5	10 x 10 hollow	5	900	A novelty cf (4)
7	12	2 x 6	6	864	
8	18	2 x 6	4	864	

Results and interpretation

Table L-3. Simulated average numbers of individuals and numbers of within-grid recaptures for eight grid layouts. Trap spacing 250m except for 2x6 units (200 m). Detection scenarios 1–3 were as for Trial 1 in Table L-1; numbers incorporate the layout numbers from Table L-2 after the decimal place.

Scenario	Grids	Layout	Nights	Trap nights	No. of animals	No. of recaptures	Recaptures per trap night
1.1	3	5 x 10	6	900	15	17	0.019
1.2	4	6 x 8	6	1152	19	22	0.019
1.3	4	5 x 10	6	1200	21	23	0.019
1.4	5	6 x 6	5	900	18	15	0.017
1.5	10	4 x 6	4	960	24	12	0.013
1.6	5	10 x 10 H	5	900	27	10	0.011
1.7	12	2 x 6	6	864	20	14	0.017
1.8	18	2 x 6	4	864	24	10	0.011
2.1	3	5 x 10	6	900	60	63	0.070
2.2	4	6 x 8	6	1152	76	81	0.071
2.3	4	5 x 10	6	1200	82	87	0.072
2.4	5	6 x 6	5	900	71	55	0.061
2.5	10	4 x 6	4	960	93	47	0.049
2.6	5	10 x 10 H	5	900	103	35	0.039
2.7	12	2 x 6	6	864	79	51	0.059
2.8	18	2 x 6	4	864	95	37	0.042
3.1	3	5 x 10	6	900	95	69	0.077
3.2	4	6 x 8	6	1152	121	90	0.078
3.3	4	5 x 10	6	1200	125	93	0.077
3.4	5	6 x 6	5	900	107	59	0.066

Scenario	Grids	Layout	Nights	Trap nights	No. of animals	No. of recaptures	Recaptures per trap night
3.5	10	4 x 6	4	960	130	49	0.051
3.6	5	10 x 10 H	5	900	139	38	0.043
3.7	12	2 x 6	6	864	101	59	0.068
3.8	18	2 x 6	4	864	119	41	0.047

Any of the conventional grid layouts 1–5 appears sufficient to provide an expected number of recaptures over 33, the presumed threshold for CV(D-hat) < 20%, for scenarios with $D = 4/km^2$ or $D = 9/km^2$. At low densities ($1/km^2$) none of the grid trapping regimes will produce enough recaptures with the (possibly conservative) g0 = 0.08, sigma = 300 m detection scenario.

Hollow grids span a larger area and catch more animals, but give fewer recaptures. They do not offer an advantage here, especially if it is hard to fit the grids in.

Small units (12 traps in two parallel rows) have the advantage of flexibility. They should be trapped for 6 nights to achieve the target number of recaptures.

For any layout, increasing the number of nights increases the number of recaptures per trap night. In this sense, 6 nights is about 40% more efficient than 4 nights.

Appendix M

Monitoring Island Fox Populations by Trapping and Spatially-Explicit Capture–Recapture: Options for Santa Cruz, Santa Rosa, and Santa Catalina

Note: An incorrect Santa Cruz Island density estimate was provided to Dr. Murray for this report; therefore, specific references to Santa Cruz Island densities in this appendix should be disregarded. All other interpretations referring to specific densities remain valid, and references to Santa Cruz Island densities in the main report are accurate.

Summary

Trapping with 9 loops or paired lines of 12 traps at 200 m spacing for 6 nights (648 trap nights) is predicted to yield the desired relative precision (CV ≤0.2) for an estimate of island population size when the fox population density is 4 km^{-2}, regardless of the size of island. Less effort is needed when density is higher. At low density (<1 km^{-2}) the required precision may be achieved only with extreme effort (>24 units of 12 traps for 6 nights).

Introduction

The aim is to design monitoring programs based on live-trapping and capture–recapture that deliver the required minimum precision for the population of foxes on each island (or part thereof in the case of Santa Catalina). The required precision is a CV[1] of 20% for the estimated population size *N*.

This report is about optimal methods for estimating local density (i.e. average density $\hat{D}$ of the fox population at the particular sites selected for sampling within each island). The ultimate interest is in the whole-island $\hat{N}$ and its estimated precision. Given $\hat{N} = \hat{D}A$, where *A* is the area of habitat on the island (assumed known), the relative precision (CV) of $\hat{N}$ is numerically equal to the relative precision of $\hat{D}$[2]. This justifies the focus on $\mathrm{CV}(\hat{D})$.

Whether a given trap layout achieves the required precision depends strongly on absolute population density and trappability. Two populations are believed currently (2005/2006) to be at very low density (Santa Cruz 0.6 km^{-2}, Santa Rosa 0.2 km^{-2}), two are at moderate density (San Miguel 1.6 km^{-2}, Santa Catalina 1.9 km^{-2}), and one is at high density (San Nicolas 9.4 km^{-2}).

[1] CV is the coefficient of variation of the estimate, i.e., the estimated sampling error of the estimate divided by the estimate itself.
[2] This strictly assumes that the relative precision of average density includes uncertainty due to the placement of sites in a non-uniform population. Local density varies among sites; the methods used here assume that variation is Poisson-distributed (variance = mean).

Except for differences due to density and trappability we expect one design (size, shape and number of trap lines; number of trapping nights) to be statistically optimal for all islands, as the same target has been set for $\mathrm{CV}(\hat{D})$ *on all islands.*

Approach to Design

We want to estimate average local density from lines or clusters of single-catch traps operated over several days. The following strategy was used to optimise the design:

1. Determine the most efficient local trap layout (shape of line, trap spacing) in terms of the number of fox recaptures expected per trap.
2. Model the precision of estimated average density as a function of the absolute number of recaptures using the selected local trap layout.
3. Determine the target number of recaptures needed to achieve the desired CV.
4. Determine the optimal means of achieving the target number of recaptures (number of units per island and number of trapping occasions) by further simulations.
5. Confirm that the optimised design yields the required CV by further simulations with full density estimation.

Only steps 2 and 5 involve the slow process of estimating density from simulated data. Steps 1, 3, and 4 use number of recaptures as a surrogate for the precision of density estimates.

Density and trappability scenarios

Trappability (more precisely, the parameters g_0 and σ of the spatial detection function) is likely to vary with habitat and density. Despite the considerable effort that has gone into trapping foxes so far, we cannot be confident about trappability at low density when it is most critical.

Previous simulations (reports of Nov–Dec 2006) used either three scenarios with a halfnormal detection function based on 'typical' points within scatterplots of previous estimates, or three scenarios with a uniform detection function.

The uniform scenarios were constructed to give a plausible inverse relation between density and territory size (assuming non-overlapping territories occupy all habitat and each territory is occupied by two foxes); they are retained as Scenarios 1–3 in the set used here (Table M-1).

The original halfnormal scenarios are replaced here with two that combine a 'best estimate' based on analyses conducted by Vickie Bakker of populations at low to moderate density on San Miguel, Santa Cruz, and other islands (Scenarios 4,5 in Table M-1).

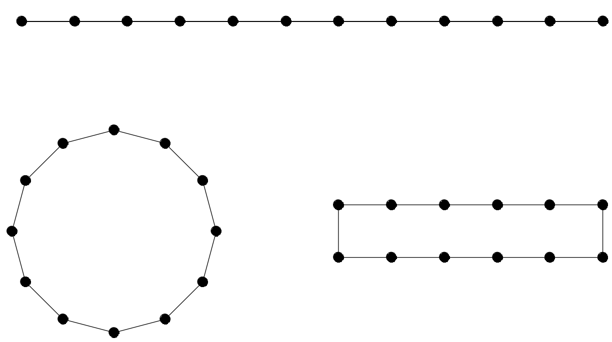
These scenarios are arbitrary and may be the weakest link in the simulations.

Table M-1. Density and trappability scenarios for simulations

Scenario	**Detection model**	**Density km^{-2}**	g_0	**σ m**	**Range size km^2**
1	Uniform	4	0.150	400	0.5
2	Uniform	2	0.075	564	1.0
3	Uniform	1.33	0.050	691	1.5
4	Halfnormal	1	0.080	300	—
5	Halfnormal	4	0.080	300	—

1 Optimal trap layout

Three trap layouts were chosen for comparison (circle, a single line, and parallel lines spaced the same distance apart as traps along each line):



Each layout was simulated with 10 traps at spacings of 200 m, 250 m, and 300m. The total number of traps was also varied in increments of 2 from 10 to 20 with 200 m spacing for each layout. Results are tabulated in Appendix M-1 and summarised (in part) in Figure M-1. They may be summarized:

- Smaller trap spacing and greater trap number are slightly more efficient, but the differences are slight.
- Paired lines and circles are preferred over single lines (increase in number of recaptures 12%, 18%, 20%, 23%, 30% for scenarios 1–5, averaged over different spacing and number of traps).
- Paired lines are similar to circles (change in number of recaptures –4%, 1%, 3%, 3%, 4% for scenarios 1–5).

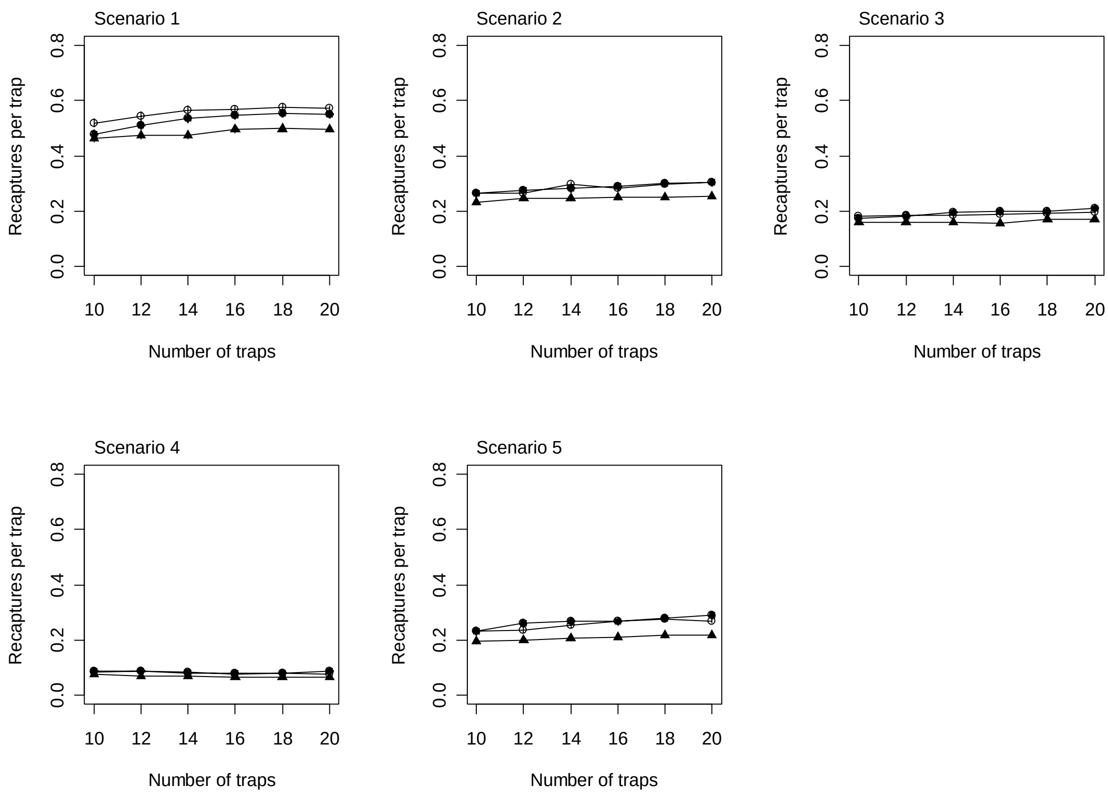


Figure M-1. Effect of trap layout on predicted number of recaptures over 6 nights; spacing 200 m throughout. ○ circle, ● paired lines, ▲ single line. Raw data in Appendix 1.

The differences between circles and paired lines with varying trap number and spacing are too slight for any single design to be described as 'optimal' on statistical grounds. Paired lines are likely to be convenient in the field; if a more open loop is preferred for operational reasons then we can be confident its sampling properties will be close to those of paired lines. Further simulations therefore use only paired lines.

The basic trapping unit is defined as twelve[3] traps arranged in two lines at a spacing of 200 m. Spacing may be increased to 250 m with only a marginal loss in terms of recaptures.

2 Precision vs number of recaptures

A general relationship was established between of the maximum likelihood density estimate (Borchers and Efford in revision) and the number of recaptures in a survey by simulating with three trapping intensities chosen to yield estimated precision near the target value. The observed pattern (Figure M-2) is similar to that from other studies with spatially explicit capture–recapture (see, e.g., Efford et al. 2004 for forest birds in mist nets).

[3] The number of traps is increased over the minimum of 10 in the draft report because of worries about bias when units are small relative to range size, and because the new scenarios 4,5 are more conservative, indicating a need for more traps in total.

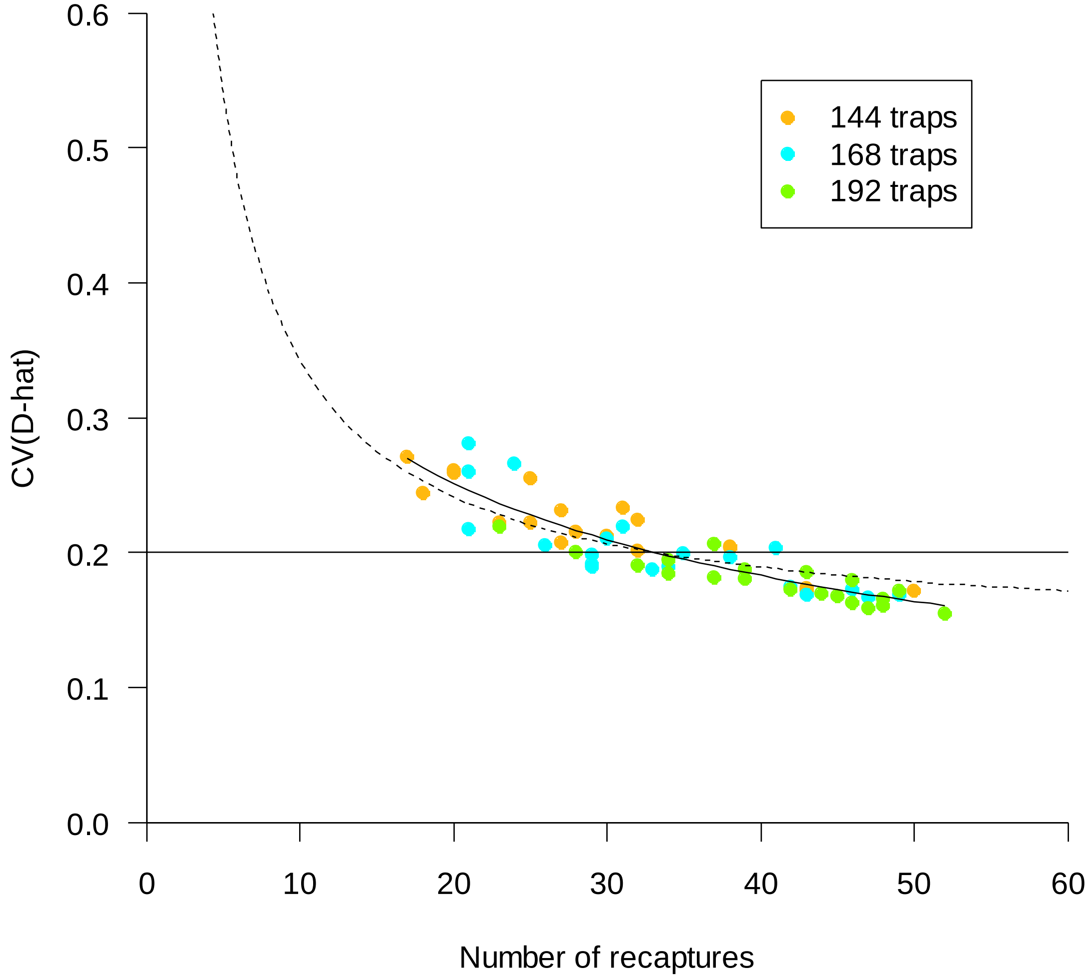


Figure M-2. Precision of density estimate as a function of the number of recaptures. Simulated data for 6 occasions and varying numbers of traps (traps were arranged in 12 units of 12, 14 or 16 traps each). D = 2 km^{-2}, g_0 = 0.08, σ = 300 m (halfnormal). Solid curve fitted by nonlinear least squares $\mathrm{CV}(\hat{D}) = 0.894m^{-0.297} - 0.116$, where m is number of recaptures; the curve intersects $\mathrm{CV}(\hat{D})$=0.2 at 33.2 recaptures. Dashed curve $\mathrm{CV}(\hat{D}) = 1.88\, m^{-0.96} +$ 0.13 was fitted to a combination of present data points and those from previous simulations (data not shown).

Table M-2. Summary of simulations for Figure M-2. Mean ± SE from 20 replicates.

No. of traps	**Recaptures**	$\mathrm{CV}(\hat{D})$
144	30 ± 2	0.220 ± 0.006
168	33 ± 2	0.203 ± 0.007
192	41 ± 2	0.180 ± 0.004

3 Target number of recaptures

From Figure M-2 we expect $CV(\hat{D}) \leq 0.20$ when the number of recaptures exceeds 33. Variation in study design, density, and trappability have only a small effect on this target. Figure M-2 also illustrates that for any one design the actual estimate of precision will vary from survey to survey even if density is constant. To buffer against this variation and ensure the target $CV(\hat{D}) \leq 0.20$ is met in most years, I recommend that trapping aims to achieve 40 recaptures on average.

4 Means of achieving target

Given a fixed design for the trapping units (12 traps in a loop or parallel line at a spacing of 200 m or perhaps 250 m), we ask how many units need to be set over how many nights to achieve the target number of recaptures. This again depends on density and trappability, so we compare multiple scenarios by simulation (Figure M-3).

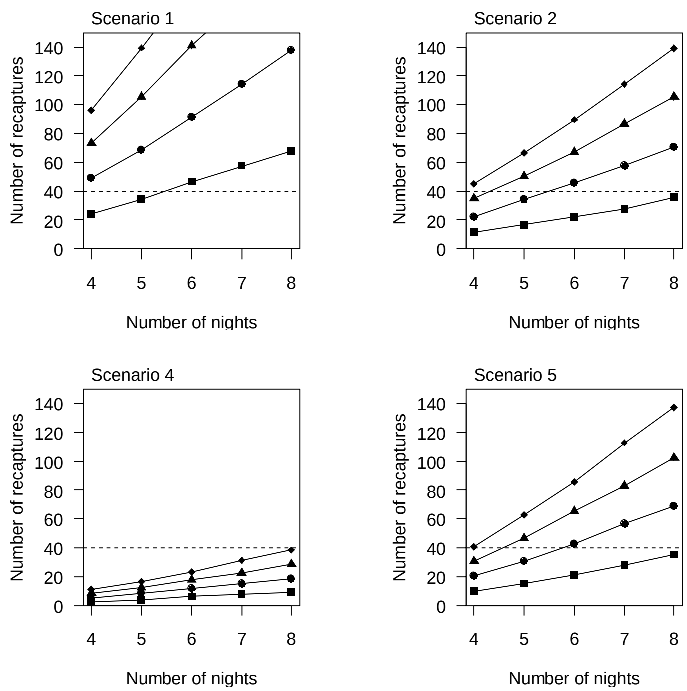


Figure M-3. Effect of trapping effort on number of recaptures. Trials with varying numbers of 12-trap paired-line trapping units trapped for varying numbers of nights. ■ 5 units, ● 10 units, ▲ 15 units, ◆ 20 units. Each point is the mean of 1000 simulations. Dashed line indicates the target of 40 recaptures. Scenarios (varying combinations of density and trappability) are given in Table M-1.

We conclude from these simulations that

- The minimum effort (5 units over 4 nights) fails under all scenarios.
- Under the most challenging scenario (D = 1/km^2, g_0 = 0.08, σ = 300 m) none of the tested levels of effort is sufficient to meet the target.

- Trapping for longer is an efficient way of adding recaptures and improving precision under all scenarios (because a greater fraction of captures are recaptures).

The number of trapping units required to meet the target of 40 recaptures was interpolated from the simulation output for varying durations of trapping (Table M-3).

Table M-3. Number of 12-trap units required to achieve target of 40 recaptures.

Nights	Scenario				
	1	2	3	4	5
4	8	18	>20	>20	20
5	6	12	19	>20	13
6	<5	9	14	>20	9
7	<5	7	11	>20	7
8	<5	6	9	>20	6

We infer that the requirement of $\mathrm{CV}(\hat{D}) \leq 20\%$ is expected to be met at densities of 1.33, 2 and 4 foxes km^{-2} when 14, 9 and 5 lines respectively are trapped over 6-nights (Scenarios 1–3; shaded cells in Table M-3). For the remaining two scenarios in which detection parameters were constant (g_0 = 0.08 and σ(halfnormal) = 300 m), no trapping regime was adequate at 1 fox km^{-2}, but the required precision could be achieved with 9.4 units over 6 nights at 4 foxes km^{-2}.

We do not have reliable estimates of the detection parameters for very low density such as on Santa Cruz and Santa Rosa in 2005/06 (<1 km^{-2}). On the assumption that detection parameters are unchanged from the standard low-density scenario (4), the number of lines should be doubled for each halving of density (Figure M-4). The required number of units may be calculated for each of the five islands given current estimates of density (Table M-4).

Table M-4. Number of 12-trap units that should be trapped for 6 nights to achieve 40 recaptures (based on Fig. M-4).

Island	**Density km^{-2} 2005/2006**	**No. of units**
Santa Rosa	0.2	–
Santa Cruz	0.6	63
San Miguel	1.6	24
Santa Catalina	1.9	20
San Nicolas	9.4	4

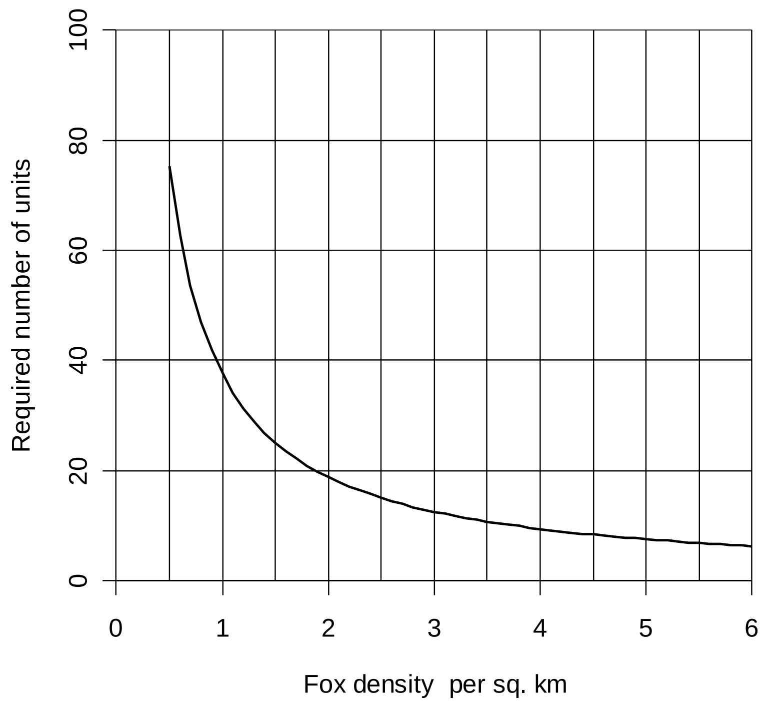


Figure M-4. Projected number of 12-trap units trapped for 6 nights needed to deliver 40 recaptures over a range of low densities, given detection parameters g_0 = 0.08 and σ = 300 m. Based on 9.4 units required for Scenario 5, assuming a linear relationship between density and number of recaptures. The curve has the equation $y = 37.6/x$.

At high density (e.g., San Nicolas 2005/06, 9.4 km^{-2}) the precision target will be exceeded.

5 Density estimation with optimised design

Simulation were performed to confirm the behaviour of the density estimator when a population of 4.0 km^{-2} was sampled with the recommended intensity (9 12-trap units for 6 nights = 648 trap nights). Detection parameters were g_0 = 0.08, σ(halfnormal) = 300 m. Trap units were assumed to be spaced far enough apart (1000 m in the simulations) that capture of an individual fox in more than one unit was very rare. The fitted model used a halfnormal detection function.

Table M-5. Estimates from simulated sampling with 9 12 trap units for 6 nights when true average density is 4 km^{-2}.

Estimate	**Mean ± SE**
Number of individuals	57.1 ± 0.6
Number of recaptures	39.6 ± 0.8
$\hat{D}$ km^{-2}	4.26 ± 0.07
CV($\hat{D}$)	0.186 ± 0.002
$\hat{g}_0$	0.075 ± 0.002
$\hat{\sigma}$ (halfnormal) m	296 ± 3

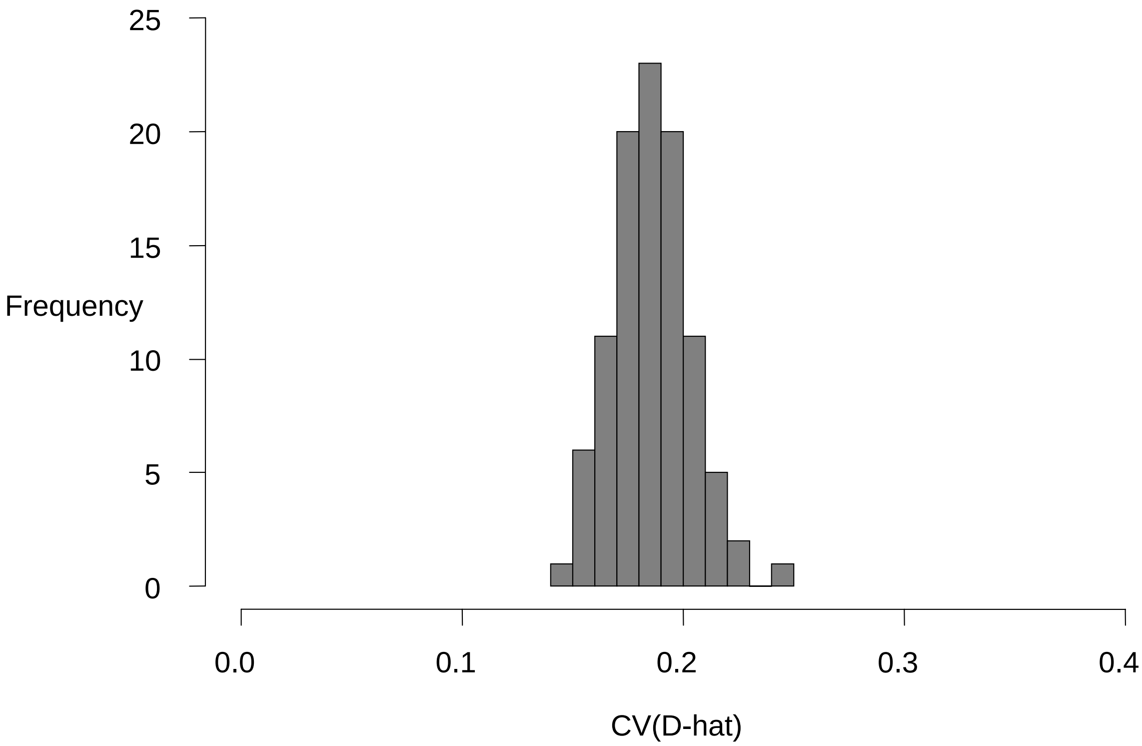


Figure M-5. Distribution of estimated precision of density estimate from 100 simulated datasets.

The estimated density showed a slight positive bias of about 6%. This is small compared with the expected sampling error, and can probably be ignored. (Other trials suggest that the bias disappears almost entirely when each unit contains 14 or more traps, but this result has not been formalized). Performance was otherwise as expected, with both the mean number of recaptures and $\mathrm{CV}(\hat{D})$ coming close to target. $\mathrm{CV}(\hat{D})$ was quite tightly distributed around its mean (Figure M-5). Nevertheless, the estimated $\mathrm{CV}(\hat{D})$ exceeded 0.2 in 19 simulations out of 100.

Derived plots

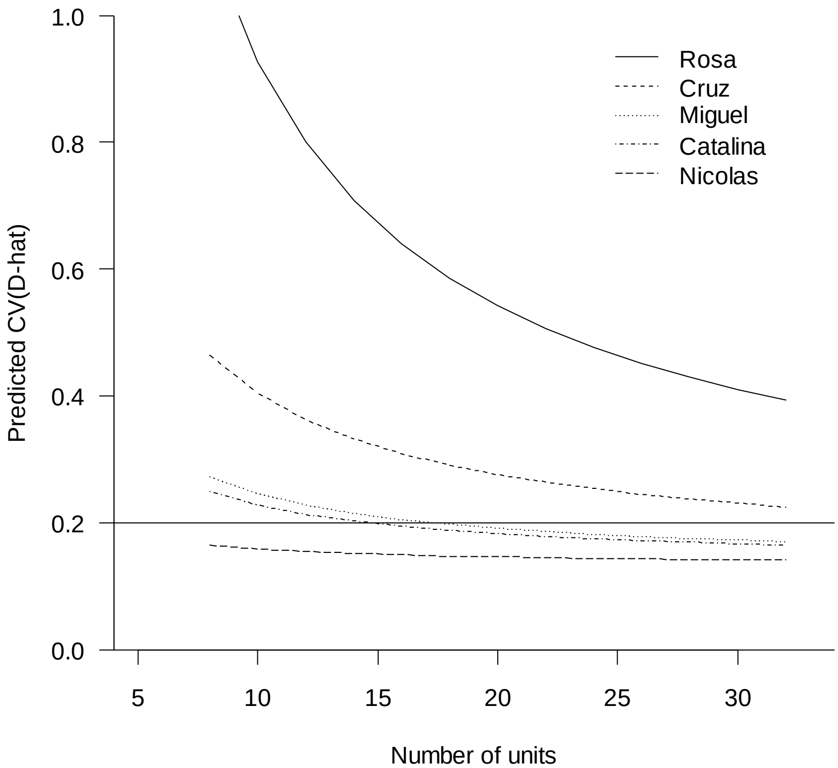


Figure M-6. Predicted precision of density estimate as a function of the number of 12-trap units trapped for 6 nights, given detection parameters g_0 = 0.08 and σ = 300 m. Each island was assumed to be at its 2005/2006 estimated density (Santa Rosa 0.2 km^{-2}, Santa Cruz 0.6 km^{-2}, San Miguel 1.6 km^{-2}, Santa Catalina 1.9 km^{-2} and San Nicolas 9.4 km^{-2}). CV was inferred from mean number of simulated recaptures m using CV = 1.88 $m^{-0.96}$ + 0.13 (cf Figure M-2). This curve is conservative for large sampling effort (i.e., correct CV is usually less than shown when CV<0.2) and the flatness of curves below the CV=0.2 line is therefore partly an artifact.

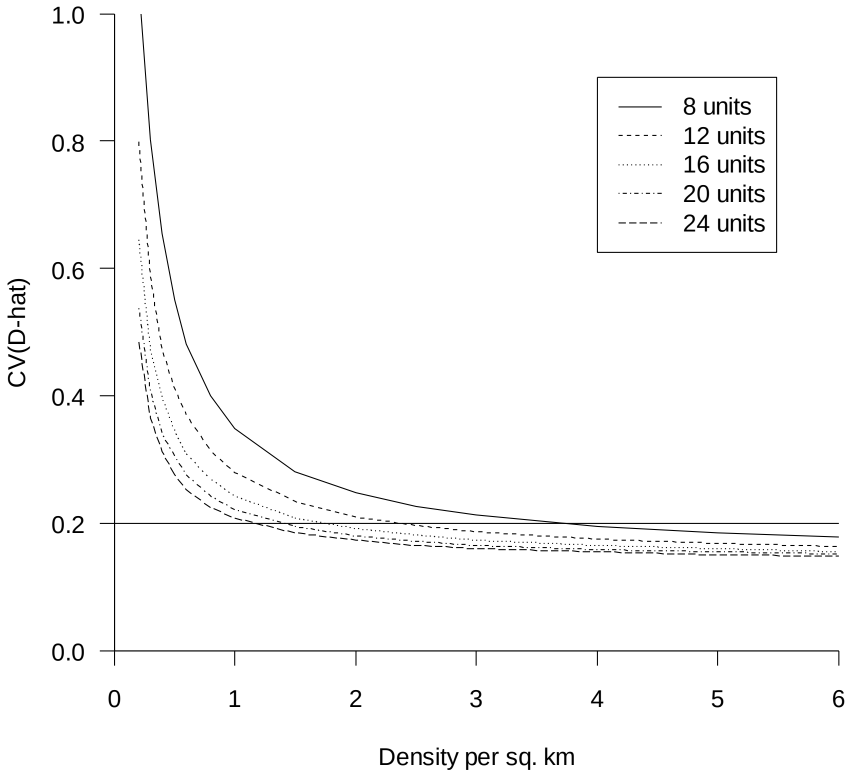


Figure M-7. Predicted precision of density estimate as a function of population density for varying numbers of 12 trap units trapped for 6 nights, given detection parameters g_0 = 0.08 and σ = 300 m. CV was inferred from mean number of simulated recaptures as in Figure M-6.

Other Comments

Scaling up from density to $\hat{N}$ should ideally be based on a probability design (e.g. random stratified or systematic) for local sampling to ensure that local density is representative of the island. Difficulties of movement off-road are said to preclude a rigorous sampling design. A partial alternative is to model the distribution of foxes. This may entail either a simple assumption of a uniform or random (Poisson) distribution across the island, or a more elaborate model of density as a function of habitat. All results reported here assume a Poisson distribution of foxes across each island.

It is commonly believed that subjectively selected sites (i.e. an 'undesigned' survey) can give unbiased estimates of trend over time. This view is mistaken because subjectively selected sites may be biased with respect either to habitat or to current population density. Either bias has the potential to produce misleading estimates of trend. Operating live-traps for island foxes away from roads is certainly arduous and relatively expensive, but this must be balanced against the dubious value of data obtained along roads.

It is important to avoid intentional or unintentional bias in the selection of sites for sampling, even if sampling does not follow a probability design overall. This may be achieved by random placement along the road network (where one exists). The potential bias is then reduced to the difference between sites near roads and far from roads, which should be evaluated by comparing the habitat in the 'accessible' and 'inaccessible' strata and, ideally, by stratified sampling of foxes themselves.

As the brief was to optimize the use of traps to monitor foxes, this report does not evaluate possible alternative methods (distance line transects, scat counts, mark-resight etc.). It is possible (but uncertain) that these methods may be better than capture–recapture for extremely low density populations.

References

Borchers, D.L., and M.G. Efford. In revision. Spatially explicit maximum likelihood methods for capture–recapture studies. Biometrics.

Efford, M.G., D.K. Dawson, C.S. Robbins. 2004. DENSITY: software for analyzing capture–recapture data from passive detector arrays. Animal Biodiversity and Conservation 27:217–228.

Appendix M-1. Effect of trap-line geometry on average predicted number of recaptures per trap over a 6-night trapping session, using single-catch traps. Mean of 1000 replicates.

			Recaptures per trap				
Geometry	**N traps**	**Spacing**	**Density & detection scenario***				
			1	**2**	**3**	**4**	**5**
Circle	10	200m	0.519	0.263	0.180	0.082	0.233
Circle	10	250m	0.510	0.253	0.164	0.084	0.223
Circle	10	300m	0.479	0.253	0.152	0.076	0.204
Circle	12	200m	0.543	0.265	0.185	0.086	0.237
Circle	14	200m	0.566	0.297	0.186	0.084	0.254
Circle	16	200m	0.571	0.283	0.190	0.077	0.269
Circle	18	200m	0.577	0.298	0.193	0.079	0.275
Circle	20	200m	0.572	0.303	0.196	0.076	0.269
Line	10	200m	0.464	0.233	0.160	0.077	0.196
Line	10	250m	0.434	0.224	0.145	0.071	0.174
Line	10	300m	0.395	0.200	0.128	0.064	0.154
Line	12	200m	0.475	0.246	0.160	0.068	0.201
Line	14	200m	0.474	0.246	0.159	0.068	0.206
Line	16	200m	0.497	0.251	0.157	0.065	0.211
Line	18	200m	0.498	0.251	0.169	0.065	0.216
Line	20	200m	0.497	0.254	0.170	0.065	0.219
Paired lines	10	200m	0.480	0.266	0.173	0.088	0.231
Paired lines	10	250m	0.491	0.266	0.174	0.082	0.231
Paired lines	10	300m	0.503	0.248	0.160	0.081	0.219
Paired lines	12	200m	0.512	0.277	0.182	0.088	0.261
Paired lines	14	200m	0.535	0.282	0.195	0.080	0.268
Paired lines	16	200m	0.546	0.292	0.199	0.080	0.269
Paired lines	18	200m	0.553	0.302	0.201	0.079	0.278
Paired lines	20	200m	0.551	0.303	0.209	0.087	0.290

* Scenarios in Table M-1

Appendix N

Number of Radiocollared Individuals Required to Detect Eagle Mortality

Prepared by

Dan Doak
University of California, Santa Cruz

Introduction

The following document estimates the number of radiocollared foxes needed to ensure that eagle-caused mortalities were actually rare, rather than just unseen due to low sample sizes. For the purposes of this document, the objective of the sampling program is assumed to be detection of a mortality rate due to eagles of ≥0.025 (2.5 %) per year. This is the approximate mortality rate associated with one eagle for low to moderate fox densities during the buildup of eagles in the 1990s. Greater rates of mortality are dangerous if fox populations are not large.

Here I estimate the sampling effort required to assure that mortality rates are low enough to be safe, <u>when we don't see any eagle-caused deaths</u>. That is, I assume that no eagle-caused deaths are observed for a year or more and the question is "does that mean we can be sure mortality rates are below the critical threshold of 2.5% annually?"

Basic Calculations

N = number of collared foxes
m* = 0.025 (the critical annual mortality rate)
p* = 1-m* (the annual probability of not being killed by an eagle)

Using binomial probabilities,

Prob(no eagle-caused deaths, with N collars and m*) = $(1\text{-m*})^N$

Using this, we can calculate the probability of seeing zero deaths for any m ≤m*, (vs. mortality higher than m*) by integrating and dividing to get a cumulative probability:

$$\Pr(m \le m^* \mid N) = \frac{\int_0^{p^*} (1-p)^N \, dp}{\int_0^1 (1-p)^N \, dp} = 1 - \left(1 - p^*\right)^{N+1}$$

Results

Achieving the desired power to detect eagle predation increases with N (Figure N-1), but required effort is substantial, with 118 collars needed over the long term to be 95% sure that eagle-caused mortality risk is at or below 0.025 when no predation is observed.

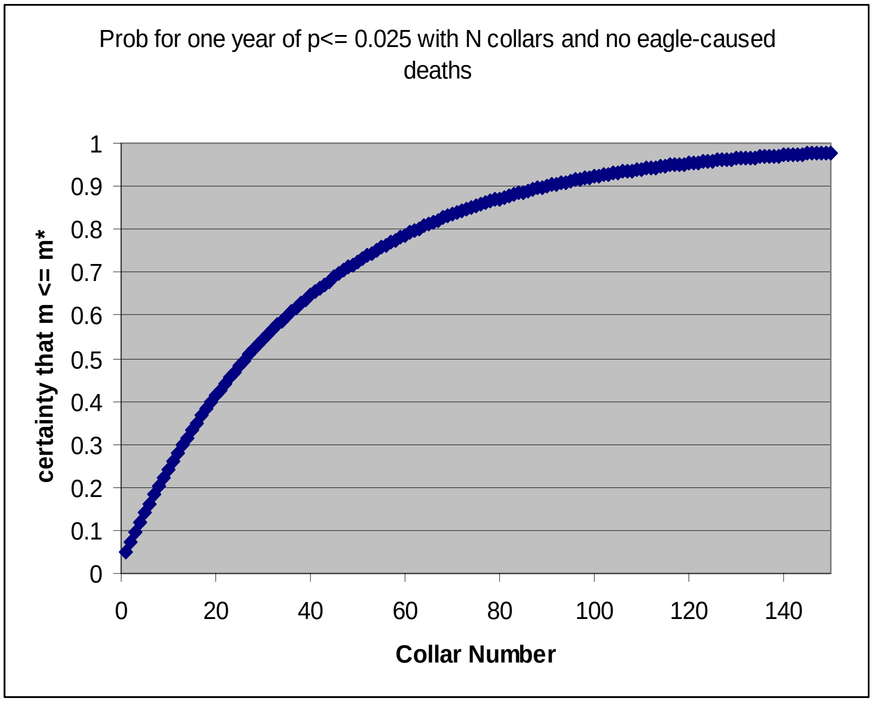


Figure N-1. Relationship between number of radiocollared foxes and certainty that true annual mortality rate is at or below 0.025 when no eagle-caused mortalities are observed.

However, we can instead track mortality rates averaged over longer time intervals. Each collared fox in each year is a separate observation, so we can roughly assume that we can use each collar-year as an independent observation and use multiple years of data to make a judgment about eagle-caused mortality. This changes the certainty criterion for low eagle mortality detection to "the certainty that mortality is on average at or below 0.025 over a 3-year time period." With this, we can reconstruct the probabilities, assuming that we have at least N collars in each year of the 3 years, which results in lower sample size requirements to achieve the revised criterion (Figure N-2). Specifically, only 40 collars are needed to yield a greater than 95% confidence that average mortality rates over 3 years are at or below 0.025

While there is nothing magical about a 3-year average for this criterion focused on detecting eagle mortality, it is nonetheless consistent with use of a 3-year average for the criterion focused on the extinction risk isoclines.

Finally, once a fox population is recovered, and thus at higher numbers, this detection criterion may be rather stringent, especially if the factors thought to drive eagle arrival have been eliminated. Thus, we can ask the same question but for a higher m* value. Figure N-3 contrasts the collars needed to assure 95% confidence for m*=0.025 and m*=0.05. For m*=0.05, only 20 or more collars will ensure 95% confidence.

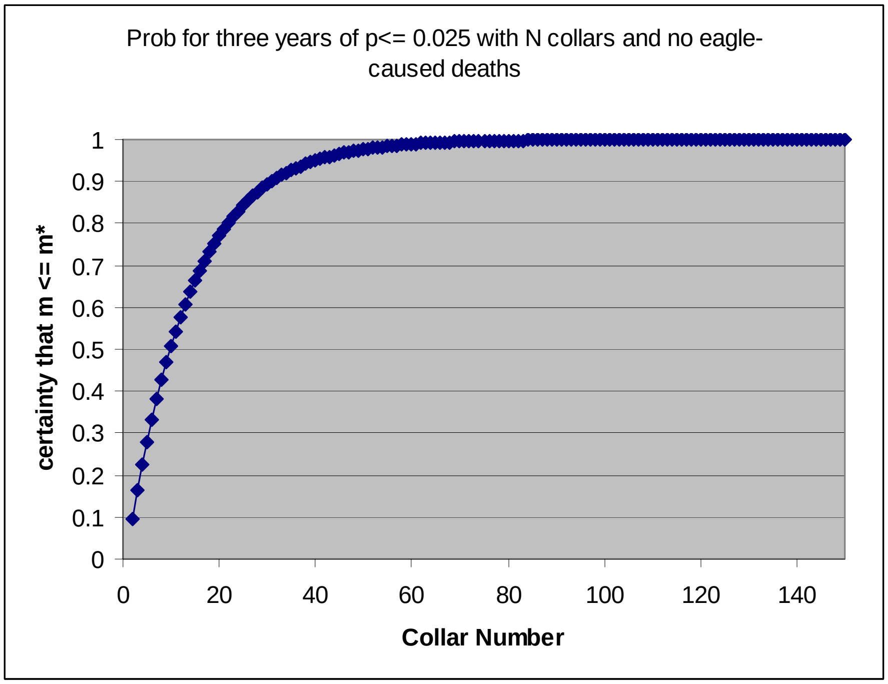


Figure N-2. Relationship between number of radiocollared foxes and certainty that true annual mortality rate, averaged over three years, is at or below 0.025 when no eagle-caused mortalities are observed.

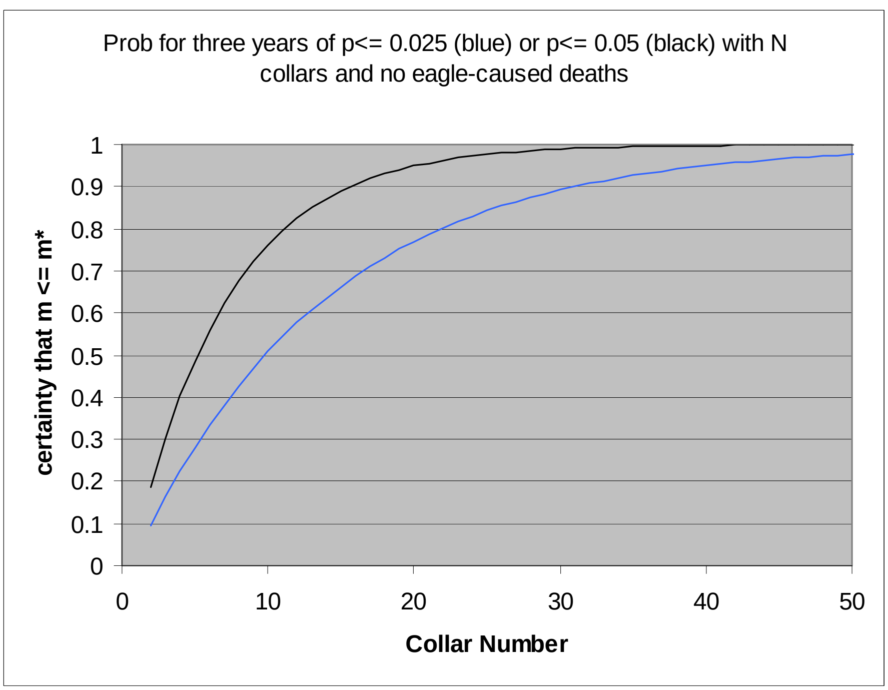


Figure N-3. Relationship between number of radiocollared foxes and certainty that true mortality rate, averaged over three years, is at or below 0.025 or 0.05 when no eagle-caused mortalities are observed.

Appendix O

Independent Statistical Review of the Monitoring Framework

The Nature Conservancy invited Dr. Gary White (Colorado State University) to provide an independent review of the draft island fox monitoring framework. Dr. White's review is included in its entirety at the end of this appendix. The following are excerpts from that review with responses that address Dr. White's comments. We carefully considered all of Dr. White's suggestions and corrections and incorporated them into the revised report as appropriate, thereby enhancing the quality of the report.

Comment 1. *I am concerned about the performance of the estimators used in Program DENSITY because of the strong assumptions required by the method used. This method assumes a constant home range size for all animals (because σ is assumed constant), and that there is little if any habitat heterogeneity (again because σ is constant in all directions). ... To summarize arguments pro and con for the 2 different monitoring schemes, the proposed monitoring scheme using DENSITY is open to bias from a necessarily simplistic model to achieve an estimate of density. Reasons include lack of models for behavioral response to capture, individual heterogeneity, and temporal variation. Other issues include constant home range size across all individuals, and no heterogeneity in habitat.*

We agree that this would be a concern if indeed σ (the movement parameter) and g0 (the detection parameter) were assumed constant. However, in the latest version of DENSITY (version 4.0), both σ and g0 can be varied through time, across space, or using session covariates. Both variables can also incorporate behavioral response to capture, individual heterogeneity, or trap-specific covariates. Some of these options are not yet implemented in the publicly available version of the program, but they are currently being developed.

Our analyses of existing grid data suggest that, even without incorporating these various forms of heterogeneity, program DENSITY yields fairly similar estimates to those of standard mark-recapture techniques using one MMDM as a buffer strip width (data not shown in report). While these results give us confidence in the methods of spatially explicit capture-recapture (SECR) analyses, we acknowledge that elongated home ranges due to movements along roads, trails, and ridges may violate the assumption that movement is constant in all directions, or that 2x6 grid configuration may alter or sample behavior in a way that biases results, a complication that would affect both traditional mark-recapture techniques and SECR. For this reason we will add recommendations for further evaluation of this possibility via future research. These evaluations should examine the implications of various home range shapes using locational data collected via GPS collars and/or computer simulation.

Comment 2. *I believe an approach superior to the DENSITY model can be developed given the data from these 40 radio-collared animals.*

This is an interesting suggestion that sounds like it could be developed into a solid method; however, it would require further development and may, for several reasons, not be feasible for our purposes:

- One part of this estimator calls for the proportion of time each collared fox spends on a grid. This requires more effort than the mortality checks we are recommending in our protocols (which require obtaining a radio signal from each animal every 1-2 days), and even the currently recommended intensity of monitoring will present a challenge for most of the islands. The added effort (either in field time to obtain locations via VHF collars or in the cost of using GPS collars) needs to be evaluated in comparison to potential benefits of this approach.
- The approach suggested by Dr. White would require that a substantial number of collared foxes are clustered in the vicinity of trapping grids. Although grid size requirements need to be evaluated, Dr. White suggested that units larger than 2x6 traps are required, which would result in fewer trapping locations on the island. The need to monitor animals for mortality, in contrast, suggests that animals should be distributed across the island. Given limited resources (for equipment and personnel), it is unlikely that managers could afford to both distribute collars for mortality monitoring and collar an additional set of animals in the vicinity of a few large grids.
- This method would require 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. Preliminary simulations by M. Efford suggest that this method may be less efficient than spatially explicit mark-recapture methods implemented in program DENSITY (i.e., it may require greater effort to obtain the same precision), but we will suggest this development as part of a research module, including evaluation via simulation and field investigation (an island such as San Clemente Island, where large grids are currently being trapped might be an appropriate location for such an investigation).

Comment 3. *...scattering traps across the island and moving them each night for 3–4 nights to achieve a sample of marked animals, followed by another 3–4 of trapping to get the ratio of marked to unmarked foxes would produce a Lincoln-Petersen estimator.*

We are not sure how or if this suggestion differs from the island-wide random trapping that we investigated thoroughly in our analyses (Appendices K, L, and M). We agree that this would be an ideal method to obtain an island-wide estimate. However, the effort involved (to set a large number of traps and move them frequently) to obtain an adequate number of recaptures makes this an infeasible method for all but possibly the two smallest islands. The manager of one of the two small islands (San Miguel) determined that this would be beyond their field crew capabilities, and we have suggested this as one scenario to be considered for the other small island (San Nicolas Island).

Comment 4. *My feeling is that 3–4 larger grids would provide better power to detect population changes than the more numerous 2 x 6 grids scattered around the island, mainly because the data are better able to generate models that can detect changes in capture probabilities from behavioral response to capture and individual heterogeneity. ... Annual estimates of recruitment and rate of population change (λ) can be estimated with the Pradel model from larger trapping grids.*

We agree that there are some advantages to using larger grids, such as (a) more flexibility to use traditional mark-recapture methods in addition to methods used in program DENSITY, and (b) facilitation of pilot tests of the radiocollar-based method Dr. White suggests.

However, as mentioned above and in the draft monitoring plan, there are several reasons why we chose not to recommend large grids on three of the five islands:

- Biologists and managers of the three large islands have told us that the steep and rugged island terrain precludes use of large grids in all but a few restricted locations, due to safety and logistic constraints.
- Larger grids may make it harder to detect area- or habitat-specific problems.
- If we did use a small number of large grids, they would likely be biased towards gentle terrain, and they would be less representative of the entire island than many small grids would collectively be.
- If we used a small number of large grids, there would need to be additional trapping across the island to collar animals for survival monitoring which, in the current recommended protocols, would likely be accomplished in the trapping on small units.

The first reason stated above is the primary driving factor in our decision to avoid large grids. Our recommended protocols would not be useful if we recommended something that the managers and biologists say would not be feasible on their island(s). In addition, the proposed recovery criteria dictate that monitoring focus on obtaining estimates of mortality rates and island-wide population size, with less emphasis on measuring trend. We have modified the text to clarify this, and to better explain the basis of this goal.

Responses to selected other issues

1. *Question about timing of trapping and whether we will be capturing young of the year*.

By late June/early July, young of the year will be captured, although their capture probabilities will likely vary for a number of reasons, including their ages. We can also use signs of lactation as a rough index of proportion of females reproducing. As Dr. White mentioned, we can also assess recruitment from the previous year by looking at yearlings trapped. After long discussions with biologists and veterinarians, we concluded that we can not trap earlier in the year because of risk to nursing pups being separated from their mothers. This is a strong concern voiced by the veterinarians involved in fox monitoring. We recognize that additional data on reproduction may have to come from other methods (e.g., cameras).

2. *Note the correct spelling of 'Lincoln-Petersen'….*

We have corrected this oversight.

3. *Several places in the document allude to using capture success or MNKA as a useful index for detecting trends. I would disagree... You could expect to see large differences in capture probabilities across time because of changes in the environment, even though fox populations have not changed. Hence, capture success might remain the same even though the population is declining, or capture success might decline even though the population is remaining stable. I suggest that even with sparse data, you can correct for changes in capture probabilities by combining data across trapping grids, years, or even islands, and make this argument in White (2005).*

We agree that capture success alone should generally not be used as an index, and have modified the text to clarify this and to advise against using MNKA at all. The Density software provides for the combining of capture probability (detection function) parameters across time and space, and this is a good way to deal with sparse capture-recapture data.

4. *There are 2 different Crooks (1994) citations, but these are not distinguished in the text.*

We have corrected this oversight.

5. *One additional recommendation is to use the known fate model in MARK to perform survival estimates for radio-collared foxes, rather than the simple Kaplan-Meier estimator.*

We occasionally reported on estimates made by others using the Kaplan Meier method, but we agree with this suggestion and will state this explicitly in the monitoring plan.

Comments on "A Population Monitoring Framework for Five Subspecies of Island Fox (*Urocyon littoralis*)"

Gary C. White, Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, Colorado 80523 USA. gwhite@cnr.colostate.edu

The report represents a tremendous amount of work and I'm impressed at the thoroughness of the process that the authors obviously went through to arrive at the proposed monitoring scheme. A large number of options were considered. Clearly considerable time, energy, and expense went into the preparation of this document.

I have 2 major comments concerning the proposed monitoring scheme for the 5 islands. First, I'm not convinced that 2 × 6 trapping grids are the best approach to monitoring on the larger islands. I am concerned about the performance of the estimators used in Program DENSITY because of the strong assumptions required by the method used. This method assumes a constant home range size for all animals (because σ is assumed constant), and that there is little if any habitat heterogeneity (again because σ is constant in all directions). I am unsure how well this approach will work given what I interpreted as fairly large changes in vegetation on these islands. As described below, you have considerable additional data with which to improve the approach.

Second, the proposed protocols are requesting that 40 foxes be radio-collared each year during the trapping period. I believe an approach superior to the DENSITY model can be developed given the data from these 40 radio-collared animals. Rather than trying to estimate the area of a trapping grid and then construct density as $\widehat{D} = \widehat{N}/\hat{A}$ (as almost all past approaches have done), I would propose fixing *A* by delineating the trapping grid, and then determining the proportion of time that radio-collared foxes then spend on the grid. To use this approach, grids larger than the proposed 2 × 6 should be used. The estimator I would suggest can be extended to include individual heterogeneity in both capture probabilities and in proportion of time spend on the grid area. Define $\widetilde{p_i}$ as the proportion of time animal i spends on the grid, and p_i^* as the probability that an animal is captured 1 or more times on the trapping grid, with $p_i^* = 1 - \prod_{j=1}^{t}(1 - \hat{p}_j)$ for *t* trapping occasions. Then for the M_{t+1} unique animals captured on the grid, density is estimated as $\widehat{D} = \sum_{i=1}^{M_{t+1}} \frac{\widetilde{p_i}}{p_i^*}$. A logical extension of this estimator is to estimate both $\widetilde{p_i}$ and p_i^* as functions of the distance to the edge (DTE) of the grid estimated from the mean capture coordinates of a fox's capture locations, because DTE would be a logical predictor of both capture probabilities (foxes on the edge of the grid would have less of their home range on the grid) and probability of occurring on the grid. The resulting estimator is then

$$\widehat{D} = \sum_{i=1}^{M_{t+1}} \frac{\widetilde{p_i}(DTE_i)}{p_i^*(DTE_i)}.$$

In the case of $\widetilde{p_i}$, a logistic regression equation can be fitted using the data for radio-collared animals, and this equation used to predict the value for animals that did not receive a radio collar based on DTE and/or other individual covariates such as age and gender. If the Huggins (1989, 1991) estimator is used to estimate population size (implemented in Program MARK, White and Burnham [1999]), the distance to edge of the grid covariate can also be used to estimate p_i^*, as well as other individual-specific covariates, such as age and sex. If enough capture occasions are available, then the Pledger mixture models (Pledger 2000) can be used to achieve the model M_{tbh} (White 2007). Therefore, issues of behavioral response to capture and individual heterogeneity can be modeled for both $\widetilde{p_i}$ and p_i^*. The proposed model with $\widetilde{p_i}$ and p_i^* is an extension of the linear model proposed in White and Shenk (2001). What appeals to me the most about this proposal is that your protocol already calls for intensive monitoring of radio-collared animals, so the collection of location data on whether radio-collared foxes continue to occupy the trapping grid is not additional effort just to estimate density, particularly with the proposed automatic monitoring systems or with GPS collars.

However, one advantage of the 2 × 6 trapping grids is that better spatial coverage of the islands is achieved. However, I'm not sure that this is a great advantage. No matter how traps are placed, the potential to get a completely valid island-wide estimate of *N* seems small. This admission does appear in the report, in that some cliff areas are considered too dangerous to sample, and other areas are too remote to sample. If you are willing to ignore the potential bias of behavioral response to capture (these foxes appear to be trap happy, and are attracted to bait) and individual heterogeneity, then scattering traps across the island and moving them each night for 3–4 nights to achieve a sample of marked animals, followed by another 3–4 of trapping to get the ratio of marked to unmarked foxes would produce a Lincoln-Petersen estimator. By pooling multiple occasions, higher capture probabilities are achieved. But the cost of this estimator is the lack of robustness to behavioral response to capture (likely a serious bias with these animals and the Lincoln-Petersen estimator) and to individual heterogeneity that cannot be explained by individual covariates (maybe less important if capture probabilities are high), plus your inability to truly sample all of the inhabited area of each of the islands.

Thus, I am suggesting that you should not claim that a completely valid island-wide estimate of *N* (and hence D) is the goal, but rather to monitor the island population with a protocol that has high power to detect trends in population size. My feeling is that 3–4 larger grids would provide better power to detect population changes than the more numerous 2 × 6 grids scattered around the island, mainly because the data are better able to generate models that can detect changes in capture probabilities from behavioral response to capture and individual heterogeneity. Further, larger grids will provide you with a measure of annual recruitment (and an associated annual estimate of λ) if the data are analyzed with the Pradel (1996) model, for which a robust-design version is currently available in MARK. Also, there is considerable development work being done to extend this model.

To summarize arguments pro and con for the 2 different monitoring schemes, the proposed monitoring scheme using DENSITY is open to bias from a necessarily simplistic model to achieve an estimate of density. Reasons include lack of models for behavioral response to capture, individual heterogeneity, and temporal variation. Other issues include constant home range size across all individuals, and no heterogeneity in habitat. However, the $\tilde{p}_i$ and p_i^* scheme I've proposed requires larger grids, and so lacks some of the "representativeness" that is achieved by scattering 2 × 6 trapping grids across the islands. In addition, collection of location data post trapping may require enough additional effort to preclude the effort. Annual estimates of recruitment and rate of population change (λ) can be estimated with the Pradel model from larger trapping grids.

The following are some more minor issues that I think worth mentioning.

1. By trapping in late June and July, you are not capturing young of the year, correct? I wonder if you don't want to monitor annual recruitment more carefully. By trapping in the late June-July period, you would obtain recruitment of yearlings (13 months old) to the breeding population, which is a useful measure. However, you may not detect a failure of reproduction for the year.
2. Note the correct spelling of "Lincoln-Petersen". Carl Petersen was Danish. Unfortunately, the literature is full of incorrect spellings.
3. Several places in the document allude to using capture success or MNKA as a useful index for detecting trends. I would disagree – capture success is a function of the capture probability parameter estimated in the capture-recapture models, and is undoubtedly a function of the health of the foxes, and the quantity and quality of their nutrition. You could expect to see large differences in capture probabilities across time because of changes in the environment, even though fox populations have not changed. Hence, capture success might remain the same even though the population is declining, or capture success might decline even though the population is remaining stable. I suggest that even with sparse data, you can correct for changes in capture probabilities by combining data across trapping grids, years, or even islands, and make this argument in White (2005).
4. There are 2 different Crooks (1994) citations, but these are not distinguished in the text.

One additional recommendation is to use the known fate model in MARK to perform survival estimates for radio-collared foxes, rather than the simple Kaplan-Meier estimator. The known fate model in MARK is a maximum likelihood extension of the K-M estimator, but allows the modeling of survival as a function of covariates, and model selection and model averaging. The K-M estimator only allows the simple $S(t)$ model. Use of the continuous time estimators, such as the Cox proportional hazards model, assume that the time of death is known exactly. Such is generally not the case with radio-tracking data. When continuous time data are made discrete and analyzed with the known fate model (equivalent to a logistic regression model), little precision is lost, and more biologically realistic models are achieved.

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