

PROGRESS IN ISLAND FOX RECOVERY EFFORTS ON THE NORTHERN CHANNEL ISLANDS

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Abstract—From 1994 to 2002, island fox (*Urocyon littoralis*) populations on San Miguel, Santa Rosa, and Santa Cruz islands declined to 15, 14, and 75-100 adult foxes, respectively, due to predation by golden eagles (*Aquila chrysaetos*). In 1999, we initiated capture and translocation of golden eagles and captive breeding of island foxes to prevent likely extinction of the three subspecies. From 1999 to 2003, 29 golden eagles were removed from Santa Cruz Island, and two from Santa Rosa Island, primarily by live-trapping with a bownet, and 5-8 eagles remained on the northern Channel Islands. Predation on island foxes continued throughout the eagle removal period, with golden eagle predation identified as cause of mortality for 22 of 26 radio-collared foxes that died on Santa Cruz Island from 2000 to 2003. In 1999 and 2000, the remaining wild island foxes on San Miguel Island (14) and Santa Rosa Island (14) were brought into captivity, with only one fox remaining in the wild on San Miguel Island. Reproductive success in captivity was similar to that observed in the wild, and was comparable to that of other endangered canids in captivity. Twenty percent of 1-2 year-old females produced a litter in captivity, as did 50% of females ≥ 2 years old. Average number of pups weaned per litter was 2.3. Seven of 14 potential founders bred on San Miguel, and 11 of 14 on Santa Rosa. Sex ratio of pups produced in captivity on San Miguel was biased toward males (19 of 25 pups). Microsatellite genotyping was used to avoid pairing of closely related animals and to examine genetic variation within the captive populations. The mean number of alleles per locus was lower for the San Miguel captive population than for the other two captive populations. Captive populations grew to 39 foxes on San Miguel Island and 56 on Santa Rosa Island by 2003. At the conclusion of the 2003 breeding season, captive fox populations were at target levels and survivorship of wild foxes on Santa Cruz Island had increased to a level (80%) required for a stable or increasing population. However, 7 of 12 captive foxes released to the wild on Santa Cruz Island in 2002-2003 died from eagle predation within 5 weeks of release. Augmentation via captive breeding will not be an effective recovery tool, at least on Santa Cruz Island, until golden eagle predation is rendered negligible.

Keywords: captive breeding, Channel Islands, golden eagles, island fox, predation, survivorship

INTRODUCTION

From 1994 to 2000, island fox (*Urocyon littoralis*) populations on the northern Channel Islands declined precipitously due to predation by golden eagles (*Aquila chrysaetos*) (Roemer et al. 2001a, Coonan et al. in press). Island foxes on San Miguel, Santa Rosa, and Santa Cruz islands

declined to near extinction as a result of hyperpredation, a phenomenon in which a novel predator is sustained by introduced prey, and drives a native species toward extinction. On the northern Channel Islands, feral pigs (*Sus scrofa*) on Santa Cruz Island supported a population of golden eagles which also preyed on native species such as island foxes (Roemer et al. 2001a, 2002). Golden

eagles, perhaps colonizers from an expanding mainland population, were first observed in significant numbers on the northern Channel Islands in the 1990s. Golden eagle colonization of the islands may have been facilitated by the absence of territorial bald eagles (*Haliaeetus leucocephalus*), which were extirpated from the Channel Islands by 1960 due to the effects of organochlorine pesticides (Kiff 1980).

By 1999, San Miguel Island foxes (*U. l. littoralis*) had declined from an estimated island-wide adult population of 450 in 1994 (Coonan et al. 2000) to 15 foxes (Coonan and Rutz 2002). Santa Rosa Island foxes (*U. l. santarosae*) declined from an estimated adult population of over 1,500 in 1994 (Roemer et al. 1994) to 14 foxes by 2000 (Coonan and Rutz 2002). The decline was not as severe on Santa Cruz Island, where island foxes (*U. l. santacruzae*) declined from over 1,400 in 1994 (Roemer et al. 1994) to less than 100 in 2000 (D. Garcelon unpubl. data).

By 1999, island foxes had undergone a decline so severe as to make persistence of the San Miguel and Santa Rosa subspecies unlikely without intervention (Roemer et al. 2001a). An expert panel convened that year by the National Park Service (NPS) recommended immediate implementation of island fox captive breeding and golden eagle removal as emergency recovery actions to prevent extinction of island foxes on San Miguel and Santa Rosa islands (Coonan 2003). The remaining island foxes were to be brought into captivity because the populations required augmentation from captive breeding to return to viable levels. Removal of golden eagles was required because eagle predation was the primary mortality factor identified for foxes in the northern Channel Islands, and wild fox populations would not recover in the face of heavy mortality from golden eagle predation (Roemer et al. 2001a). While the emergency recovery actions were implemented, the following recovery objectives were developed for the Park's island fox recovery strategy (Coonan 2003): 1) remove or minimize island fox mortality factors, especially golden eagle predation and canine disease; 2) augment critically low wild fox populations via captive breeding and release; 3) establish management and monitoring programs to protect wild fox populations; and 4) restore natural ecosystem

elements and processes to the northern Channel Islands. This paper describes the methods and results of recovery actions implemented during 1999 through 2003.

METHODS

Establishment of Captive Breeding Colonies

We captured foxes using welded-wire box traps (23 x 23 x 66 cm, Tomahawk Live Trap Co., Tomahawk, WI) baited with dry cat food and a fruit scent (Knob Mountain Raw Fur Co., Berwick, PA). Captured foxes were protected from the elements by careful placement of traps, and by a burlap cover on each trap. Traps were deployed in transects or clusters. Observation of sign (feces or tracks) and images from remote cameras were used to determine if foxes were present in an area. Captured foxes were marked with passive integrated transponder (PIT) tags (Biomark, Seattle, WA) inserted subcutaneously between the scapulae, and were transported to captive enclosures.

Captive breeding pens were constructed of pre-assembled 6 by 10 ft (1.8 x 3.1 m) wall panels and 10 x 10 ft (3.1 x 3.1 m) roof panels of chain link fencing material. A ground skirt of welded wire was placed beneath the pen walls to prevent foxes from escaping via excavation. Pen size and configuration varied, but a typical pen was U-shaped or Z-shaped to support a roof, and was 500-600 square feet (45-54 m²) in area. Pens were furnished with plywood denboxes, climbing structures, and items such as buried PVC pipe for behavioral enrichment. Pens were separated from each other by distances of 3-50 m.

By 2003, all foxes of the San Miguel Island and Santa Rosa Island subspecies were in captivity. To reduce the likelihood of disease or other catastrophic agent eliminating the captive populations, we held foxes in two separate locations on each island. Due to continuing eagle predation, the NPS and The Nature Conservancy established an island fox captive breeding program on Santa Cruz Island in 2002. Because augmentation of an existing wild population requires less supplementation than restoring an entire population, as on San Miguel and Santa Rosa islands, the facility size (10 pairs) on Santa Cruz Island was half that of the other islands

We developed a captive fox diet comprising high-quality dry dog food (25-28% protein, 10-12% fat) and supplemented with hard-boiled eggs, fruits and vegetables. Once a week, foxes were fed live deer mice (*Peromyscus maniculatus*) and/or dead coturnix quail (*Coturnix coturnix*). The amount of food given daily was 3-4% dry weight of the animal's body weight. Captive foxes were given annual veterinary examinations, and blood samples were taken annually for serology and complete blood chemistry. Beginning in 2002, captive foxes were vaccinated against canine distemper virus with a Canary pox vectored recombinant vaccine (Purevax Ferret Distemper vaccine, Merial, Inc., Athens, GA) used successfully on Santa Catalina Island foxes (Timm et al. 2002).

Captive foxes were housed primarily as mated pairs. To increase the probability of selecting pairs that were mated in the wild, we used data obtained from spatial associations determined via radiotelemetry (e.g., likely pairs based on home range overlap) and capture history to pair animals that were thought to be mated in the wild. If animals paired in captivity did not produce a litter after 2 breeding seasons, the pair was split and the individuals re-paired with other individuals.

To estimate genetic variability in the captive populations and minimize the potential for inbreeding, we determined relatedness among captive island foxes by genotyping across five tetranucleotide microsatellite loci (Gray 2002). The genomic data were used to estimate mean heterozygosity, mean inbreeding, and mean number of alleles per locus. We used the program Population Management 2000 (Lacy and Ballou 2002, Pollack et al. 2002) on island fox studbook (pedigree) data to quantify founders and descendants, and estimate relative contribution of founders for the San Miguel and Santa Rosa captive populations.

We determined target captive population size via demographic modeling (Roemer et al. 2001b). Program VORTEX was used to set wild population ranges with minimal chance of extinction, and then an augmentation schedule was constructed that would reach a minimum viable population with an acceptable extinction risk within 10 years. Finally, captive population sizes were chosen that would produce enough pups to meet the annual

supplementation rate in the augmentation schedule. In this manner, a captive population target of 20 pairs was chosen for San Miguel and Santa Rosa islands. The population vital rates identified through demographic modeling were incorporated as recovery criteria in the NPS island fox recovery strategy (Coonan 2003). Generally, annual survival of >80%, when coupled with typical recruitment and annual augmentation of 12-20 foxes from captivity, will recover island foxes to a population level of 200-300 adults within 10 years.

We began experimental releases of captive foxes on Santa Cruz Island and Santa Rosa Island in 2002-2003 to investigate survival of captive foxes released to the wild. Foxes selected for release were genetically well-represented in the captive populations. Foxes were released as mated pairs which had been housed together for >1 yr, or as groups of unpaired animals which had been placed together in a socialization pen for 10-18 d. Foxes were outfitted with radiotelemetry collars and were released directly from small portable kennels. Feeding stations provided supplemental food, and foxes were recaptured at intervals of 1 week and one month to determine physical condition. Foxes were returned to captivity if they had lost >20% of their release weight, and then re-released after sufficient weight gain. For the 2003 releases, if $\geq 50\%$ of the released foxes died, the remaining foxes were recaptured and returned to captivity.

Golden Eagle Live Capture and Removal

In 1999, the NPS established a cooperative agreement with the Santa Cruz Predatory Bird Research Group for relocation of golden eagles from the northern Channel Islands. The primary technique used a dug-in, radio-controlled bownet placed in areas that eagles were known to visit (Jackman et al. 1994). Bait used included dead feral pigs, live feral pigs, and live rabbits. The bownet was set in place prior to dawn. If an eagle alighted on the prey, the net was deployed via radio signal from a distant blind. Captured eagles were banded, measured, placed in a sky kennel, and kept in a cool quiet room until transport. The first 12 eagles captured were fitted with satellite and conventional radiotelemetry transmitters. Most eagles were flown off the island by the next morning, and then driven to or flown by

commercial airliner to a release site. Relocated eagles were released into optimum golden eagle habitat as far away from the Channel Islands as practicable, on the eastern side of the Sierra and in the northeastern corner of California. Releases occurred usually within 48 hours of capture.

A study was initiated on Santa Cruz Island in December 2000 to monitor survivorship in wild island foxes (Dennis et al. 2001a, 2001b, 2002a, 2002b, Newman et al. 2002a, 2002b, 2002c, 2003). A sample of approximately 25 radiocollared wild foxes was maintained, representing about one-quarter to one-third of the approximately 75-100 wild adult foxes estimated to remain on the island. Radiocollared foxes were located several times per week to determine survival status. Upon receiving a mortality signal from a collar, each carcass was retrieved from the field and sent for necropsy to the Veterinary Medical Teaching Hospital, University of California, Davis. The mortality data were used to estimate annual survivorship of island foxes using the non-parametric Kaplan-Meier procedure with staggered entry (Pollock et al. 1989).

RESULTS AND DISCUSSION

Captive Breeding

In 1999 and 2000, the remaining wild island foxes on San Miguel Island (14) and Santa Rosa Island (14) were brought into captivity, with only one fox remaining in the wild on San Miguel Island and none on Santa Rosa Island. In 2002, captive breeding was initiated on Santa Cruz Island with 10 captive pairs. Only four foxes brought into captivity on San Miguel were male. In 2003, the

lone remaining fox on San Miguel was brought into captivity. Captive populations grew to 39 foxes on San Miguel Island and 56 on Santa Rosa Island by 2003. The captive population target of 20 pairs was reached by 2003 on Santa Rosa (21 pairs) but not on San Miguel (16 pairs). The annual rate of population increase for the San Miguel ($\lambda = 1.3$) and Santa Rosa ($\lambda = 1.2$) captive fox populations is comparable to that of captive Mexican gray wolves (*Canis lupus baileyi*) ($\lambda = 1.14$; Siminski 1997). The increase of both island fox subspecies from starting populations of 14 to their current population levels exceeds the rate of growth for captive red wolves (*Canis rufus*), which increased from an initial population of 17 individuals in 1977 to 65 individuals in 1985 (Phillips 1995).

By 2003, 7 of 14 potential founders (wild-born foxes) had bred on San Miguel, whereas 11 of 14 potential founders had bred on Santa Rosa (Table 1). The number of founder genome equivalents, and founder genomes surviving, was higher on Santa Rosa Island than on San Miguel Island. Mean heterozygosity was similar in the two captive populations, but mean number of alleles was less for San Miguel Island foxes (2.2) than for Santa Rosa Island (3.0) or Santa Cruz Island foxes (3.6). Because allelic diversity is typically lost more rapidly in captive populations than heterozygosity, at least 10 founders are required to sample >95% of a source population's heterozygosity; a founder size of 25-50 individuals would be required to adequately retain allelic diversity (Ballou and Foose 1996). The number of founders for Santa Rosa Island (11) meets the rule of thumb for heterozygosity, but the number of founders for San Miguel Island (7) does not.

Table 1. Demographic and genetic characteristics of captive island fox populations on the northern Channel Islands, 2003.

	San Miguel	Santa Rosa	Santa Cruz
Number in captivity	39	56	30
Males:females	23:16	21:35	16:14
Pups born	25	44	15
Founders (Potential Founders)	7 (14)	11 (14)	-
Living Descendants	25	42	-
Founder Genome Equivalents	4.48	7.51	-
Founder Genomes Surviving	6.44	10.18	-
Mean Heterozygosity	0.322	0.350	0.43
Mean Inbreeding	0.126	0.326	0.092
Mean # of alleles per locus	2.200	3.000	3.600
# of loci used	5	5	5

Mean heterozygosity was lower on San Miguel and Santa Rosa islands than on Santa Cruz Island, where the decline was not as severe. Mean inbreeding was also lower on Santa Cruz Island than on the other two islands. Captive island fox mean heterozygosity values and average number of alleles were lower than values for larger, out-bred populations of non-endangered species, and fall within ranges typical of endangered species (Frankham et al. 2002).

Sex ratio of pups produced in captivity on San Miguel Island was biased toward males (19 of 25 pups), perhaps as a result of inbreeding. Captive koalas (*Phascolarctos cinereus adustus*) in Queensland, Australia, had a male-biased sex ratio in offspring, likely due to the expression of deleterious alleles in the homozygous female X chromosome (Hook and Schull 1973, Worthington Wilmer et al. 1993). However, as with the captive koalas, captive island foxes exhibited no other apparent symptoms of inbreeding, such as reduced juvenile survivorship (Ralls et al. 1988). Island foxes have always existed at relatively low population sizes, and have undergone considerable fluctuation, with subsequent loss of heterozygosity and allelic variation (Wayne et al. 1991). Low genetic diversity is a hallmark of the species, and, like the Queensland koalas, island foxes may have a reduced susceptibility to inbreeding depression. For example, San Nicolas Island foxes (*U. l. dickeyi*) are essentially monomorphic at numerous genetic loci (Wayne et al. 1991), likely due to a population bottleneck in the 1970s (Laughrin 1980). However, the San Nicolas population currently has the highest density and population size of all six island fox subspecies (Schmidt and Garcelon 2003).

Overall, reproductive output in captivity was similar to that observed in the wild. The average number of pups weaned in captivity was 2.3 ($n = 35$ litters), which is slightly higher than the average number of pups weaned in the wild on San Miguel Island from 1993 to 1998 (2.0, $n = 34$ litters) (Coonan et al. in press). The proportion of females that produced litters was also similar to that observed in the wild. In captivity, 31 of 74 annual pairings (41.9%) produced litters, compared to 42.8% in the wild (54/126 annual pairings).

Female age was a factor in reproductive success. The proportion of juvenile (1-2 year-old)

females that bred in captivity was 22.7% (5/17), similar to the 19% observed in the wild (Coonan et al. in press). The proportion of older (>2 years old) females that bred in captivity was 50% (26/52), which is less than the 60% observed in the wild. This is primarily due to the failure of some potential founder females to reproduce in captivity.

Mate history affected reproductive success as only 32.5% (13/40) of first-year matings were successful, whereas 50% (17/34) of second, third and fourth-year matings were successful. Captive-born females had less reproductive success than wild-born females. Only 1 of 18 matings involving captive-born females produced a litter, whereas the success rate for wild-born females was 53.6% (30/56). However, many of the captive-born females were juveniles, for which breeding success is low in captivity, as it is in the wild (Coonan et al. in press).

In December 2002, three captive-born juveniles were released to the wild on Santa Cruz Island. In November-December 2003, six juveniles and three yearlings were released to the wild on Santa Cruz Island, and between November 2003 and January 2004 12 captive foxes of various ages were released on Santa Rosa Island. Two of the foxes released on Santa Rosa were returned to captivity when post-release monitoring indicated they had lost >20% of their weight at release. They were re-released to the wild after appropriate weight gain. Released foxes began utilizing feeding stations in the first week following release, and examination of fecal material indicates that foxes were including natural foods such as insects and rodents in their diet in the first week.

Golden Eagle Removal

Golden eagle sightings were most numerous on Santa Cruz Island. Therefore, survey and capture efforts were focused on that island. Thirty-one golden eagles were captured and relocated from 1999 through June 2003, including 29 from Santa Cruz Island and two from Santa Rosa Island. None of the 12 telemetered eagles returned to the islands, and only one crossed the Sierra Nevada Mountains from its release site (Latta 2001, 2002). As breeding adults might be expected to return to their territories (Philips et al. 1991), the fact that they did not suggests that release locations were suitably distant, and perhaps that habitat quality for

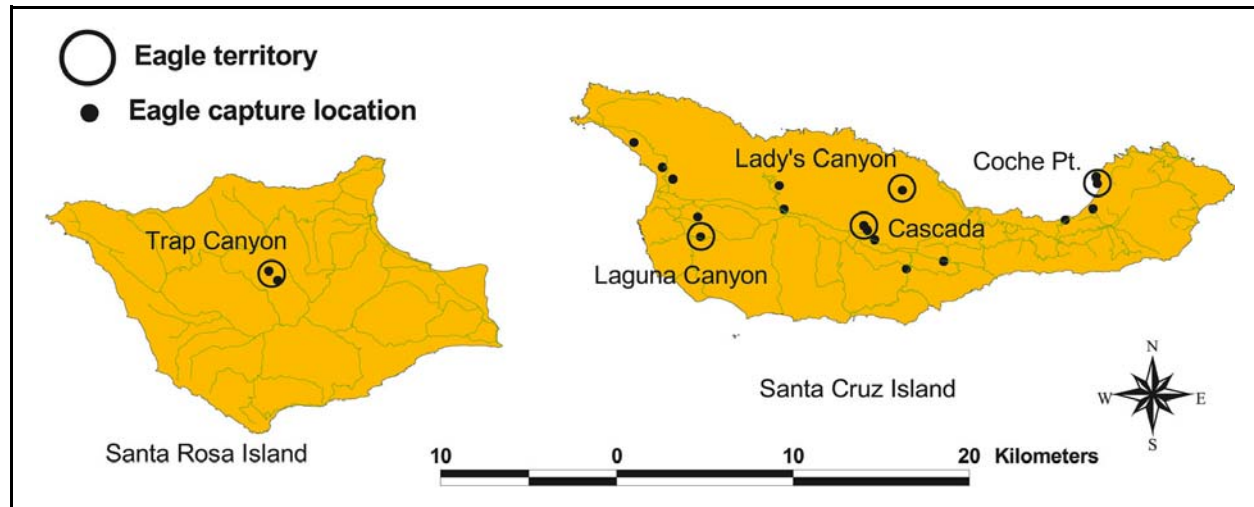


Figure 1. Golden eagle capture locations and golden eagle territories with successful nests, Santa Rosa and Santa Cruz Islands, 1999-2003.

golden eagles on Santa Cruz Island is lower than habitat quality in the release areas.

The relocated eagles included 17 adults or near adults, six subadults, three juveniles, and five nestlings. At least four nests were successful from 1999 to 2003, including two on Santa Rosa Island (Fig. 1). Excavation of several nests in one eagle territory on Santa Rosa Island revealed considerable numbers of island fox remains in the lower, older layers. Because golden eagles only deliver prey to nests with young, the nest likely successfully reproduced prior to 2000, when all foxes were brought into captivity. The remains of mule deer fawns (*Odocoileus hemionus*) in the excavated golden eagle nests on Santa Rosa Island suggest that deer are also important live prey for golden eagles during the nestling period.

A number of eagles were left on the islands after annual trapping efforts (Fig. 2). At the end of trapping efforts in 2003, as many as five eagles remained on Santa Cruz Island, and three on Santa Rosa Island. Six of these were known to have bred or to have attempted breeding. Breeding birds may be the most problematic for island foxes, as production of young by golden eagles requires access to live prey (Watson and Langslow 1989). Thus, island foxes may be at higher risk of predation during spring and early summer.

The contribution of immigration to the island eagle population is unknown. Reconstruction of the island golden eagle population suggests that a

limited number of source pairs may be responsible for most of the approximately 39 known individuals (B. Latta unpubl. data). Analysis of relatedness from DNA genotyping could potentially determine whether one or two founder events could account for the current golden eagle population on the northern Channel Islands. If immigration is limited, then removal of the existing eagle population may effectively mitigate predation on island foxes. If significant recruitment from the mainland occurs, then eagle removal will necessarily be a long-term recovery action, until removal of feral pigs and/or establishment of bald eagles make the northern Channel Islands less desirable habitat for golden eagles.

Effect of Eagle Predation on Island Foxes

The survivorship of radiocollared foxes on Santa Cruz Island is a measurement of the success of eagle removal in reducing predation as a mortality factor. From December 2000 through December 2003, 26 radiocollared foxes died, and golden eagle predation was identified as the cause of mortality for 22 of the 26 foxes. Over the study period wild fox mortality due to golden eagles declined, and annual survivorship of wild island foxes increased from 61% to 80%, likely due to removal of golden eagles (Fig. 2). Annual survivorship of 80% is the level determined by demographic modeling to be necessary for a stable or increasing fox population (Roemer et al. 2001b,

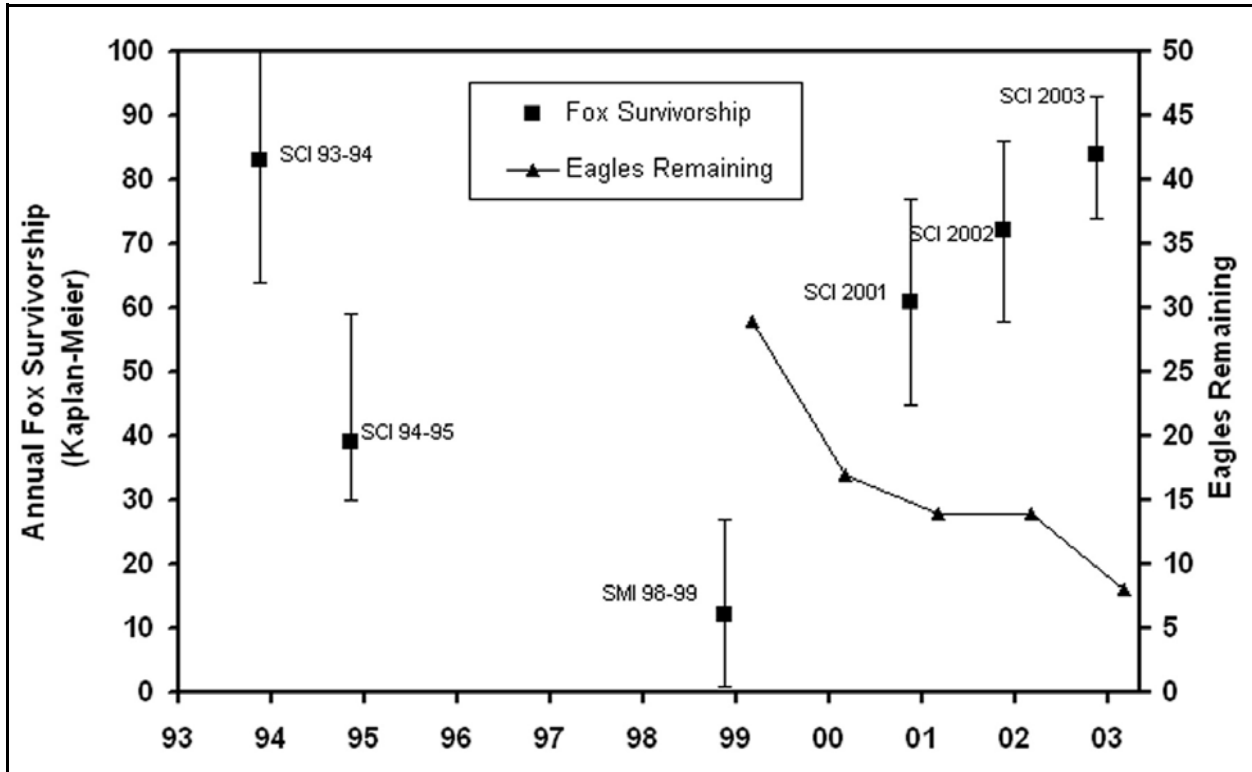


Figure 2. Annual survivorship of wild island foxes, with 95% confidence interval, and number of golden eagles annually remaining on the northern Channel Islands. SCI = Santa Cruz Island, SMI = San Miguel Island. Santa Cruz Island fox survivorship data from 1993-95 are from Roemer et al. (2001a). San Miguel Island data are from Coonan et al. (in review).

Coonan 2003). Survivorship in 2003 approached island fox survivorship values recorded prior to the decline of island foxes (Fig. 2).

However, initial survival was poor for captive foxes released to the wild on Santa Cruz Island. Two of three captive juveniles released in December 2002 died from eagle predation within two weeks of release. Five of nine captive foxes released on Santa Cruz Island in November-December 2003 died from eagle predation within five weeks of release. Because mortality for the 2003 Santa Cruz Island release exceeded the 50% threshold for return to captivity, the remaining four foxes were recaptured in January 2004.

On Santa Rosa Island, one of the 12 foxes released to the wild in November-December 2003 died from eagle predation. Five of the 12 released foxes were returned to captivity on Santa Rosa because their activity areas included the captive facilities, and interactions with captive foxes resulted in injuries to both captive and wild foxes. Post-release movements on Santa Rosa Island were generally away from the release sites on the north-

western portion of the island. Two foxes dispersed 7.2 km and 15.4 km from the release site, respectively, one to the southeast coast and one to the southwest coast of the island. Other foxes dispersed back to the general area of the captive facilities. The one Santa Rosa Island fox killed by golden eagle predation had established a use area in the vicinity of a nesting pair of golden eagles in Trap Canyon.

The poor survival of captive foxes released to the wild on Santa Cruz Island may be due to behavioral differences between wild foxes and those held in captivity. The latter may have more diurnal activity patterns, may frequent more open areas, or may move more than wild foxes. Activity patterns of wild foxes on Santa Cruz Island are currently being investigated (R. Woodroffe pers. comm.). Future releases on Santa Cruz Island are likely to experience similar levels of predation mortality, unless the golden eagle population is further reduced, or captive foxes learn to avoid predators. Although it may be possible to assess survival probability of released foxes according to behavioral traits observed in captivity (Bremner-

Harrison et al. 2004), the probability of successfully training captive foxes to avoid predation (Griffin et al. 2000) is unknown.

Prospects for Recovery of Island Foxes

In the absence a catastrophic mortality source such as eagle predation or canine distemper virus, island fox populations can exhibit considerably high survivorship (Kohlmann et al. 2003, Coonan et al. in press). Prospects for recovery are therefore good for the island fox populations on the northern Channel Islands if eagle predation is sufficiently ameliorated and canine diseases held at bay. Island foxes have reproduced successfully in captivity, and are at or close to target population sizes that would allow releases into the wild. However, despite the removal of 31 eagles from 1999-2003, golden eagles still persist on the Channel Islands and still prey upon island foxes. The poor survival of foxes released from captivity on Santa Cruz Island suggests that augmentation from captive breeding, at least on that island, will be ineffective as a recovery action until eagle predation is further decreased. Eagle removal efforts to date have failed to remove all eagles, thus it is unknown whether future efforts will maintain eagle predation at a level sufficient for recovery of foxes. Since even a limited number of golden eagles can potentially drive an island fox population toward extinction (Roemer et al. 2002), the prospects for island fox recovery decrease considerably when a large number of eagles remain on the islands.

The reintroduction of bald eagles to the northern Channel Islands and the removal of feral pigs from Santa Cruz Island may ultimately discourage golden eagle use of the islands. There are currently >20 young bald eagles on the northern islands as a result of releases in 2002-2004 (Garcelon 2004), but whether bald eagles will truly discourage golden eagle use of the islands is speculative. In the same vein, removal of feral pigs from Santa Cruz Island is scheduled to commence in fall 2004, but short and long-term golden eagle response to pig removal is unclear (Courchamp et al. 2003). In the continued presence of golden eagles, recovery of island foxes will depend upon favorable ecological outcomes well outside the scope of fox recovery actions.

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