FINAL REPORT

POTENTIAL FOR DENNING BEHAVIOR TO FACILITATE TRANSMISSION OF SARCOPTIC MANGE IN ENDANGERED SAN JOAQUIN KIT FOXES

Prepared for the
Arthur L. & Elaine V. Johnson Foundation

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October 2023

SUMMARY

San Joaquin kit foxes (*Vulpes macrotis mutica*) are listed as Federally Endangered and California Threatened due to profound habitat loss. A robust population of San Joaquin kit foxes occurs in the urban environment of Bakersfield, California. This population was thriving until 2013 when sarcoptic mange was detected and rapidly spread throughout the population causing a significant decline in kit fox abundance. Mange also was detected in the small urban kit fox population in nearby Taft beginning in 2019. Interestingly, mange has not been detected in any non-urban populations.

Kit foxes use dens on a daily basis. Two or more kit foxes sometimes use the same den concurrently which provides an opportunity for mange transmission. Also, sarcoptic mange mites can live off-host under favorable conditions (e.g., cool temperatures, high humidity) and kit fox dens have been found to support such conditions. Thus, kit foxes potentially can be infected by using a den that has been used previously by an infected fox.

To assess the potential role of dens in the transmission of mange among kit foxes, we intensively monitored den use patterns of 37 kit foxes on and near the 152-ha California State University-Bakersfield campus. All of the foxes had unique dye marks and 20 also were fitted with radio-collars. Collared foxes were tracked to dens and then those dens were monitored for one week using automated field cameras. We determined the number of foxes using a given den for two, four, and seven days after collared fox was first detected using the den. These intervals corresponded to the estimated time mites could survive in the dens in summer, across all seasons, and in winter, respectively. We also determined the number of foxes that were in the den concurrently with the collared fox during these intervals. Finally, for each collared fox, we determined the number of dens it used over a 120-day period, the number of other foxes using these dens within a week of use by the collared fox, and the number of foxes concurrently using the den. The 120-day interval corresponds to the estimated time a fox might survive after contracting mange.

Collared foxes used 68 dens during the study and 390 one-week monitoring sessions were conducted. The proportion of sessions that other foxes used the same den as the collared within two, four, and seven days was 78.5%, 84.4 %, and 89.0%, respectively. The mean number of other foxes using the dens during the three intervals was 1.8, 2.2, and 2.5, respectively. Also, an average of 1.8 foxes were detected in a den concurrently with the collared fox during each week-long session. These values did not vary among seasons although den sharing tended to trend higher in winter. Females shared dens significantly more than males. During the 120-day intervals, collared foxes used a mean of 7.6 dens, 9.8 other foxes used the same dens within one week, and 7.3 foxes used the dens concurrently with the collared foxes.

These results indicate that the potential for kit foxes to transmit mange through den sharing in the urban environment is considerable. This may explain the rapid spread of mange throughout the urban kit fox population. Lower fox densities and spatial overlap in non-urban habitats likely results in less den sharing between social groups and may explain the lack of detections of foxes with mange in these habitats.

ACKNOWLEDGEMENTS

We gratefully acknowledge field assistance on this project provided by Francisco Ruiz Ponce, Isaac Owens, Erika Noel, students in the Hall Wildlife Ecology Lab, Tanner Lichty, Jacob Spriester, and Steven Satter. Funding for this project was provided by the Arthur L. & Elaine V. Johnson Foundation. Additional support was provided by a grant from the U.S. Bureau of Reclamation's Central Valley Project Conservation Program. We thank the California State University-Bakersfield for allowing us to conduct this study on their campus.

In efforts to trap and treat foxes with mange, ESRP staff have been assisted significantly in their efforts by staff from the California Department of Fish and Wildlife, staff from McCormick Biological, Inc., and students from the California State University-Bakersfield. Staff at California Living Museum have been critical collaborators in treating and rehabilitating kit foxes with advanced cases of mange. We thank Jaime Rudd for reviewing a draft of this report.

INTRODUCTION

The San Joaquin kit fox (*Vulpes macrotis mutica*) historically ranged in arid shrub and grassland habitats throughout central California's San Joaquin Valley. Widespread agricultural, industrial, and urban development over the past 100 years has resulted in extensive habitat destruction and extirpation of San Joaquin kit foxes throughout much of their range (U.S. Fish and Wildlife Service [USFWS] 1998, Cypher et al. 2013). Consequently, the San Joaquin kit fox was listed as Federally Endangered and California Threatened, and is now largely restricted to remnant habitat in the western and southern margins of the San Joaquin Valley and the Carrizo Plain region. Remaining foxes likely number less than 5,000 and persist in a metapopulation consisting of three main populations and less than a dozen, smaller satellite populations (Cypher et al. 2013; USFWS 2020*a*, 2020*b*). Historically, disease had not been identified as a significant threat to San Joaquin kit foxes (USFWS 1998).

One of the largest remaining populations of San Joaquin kit foxes occurs in the city of Bakersfield. This population is important for the conservation and recovery of this species as it serves as a hedge against catastrophic events in natural lands, enhances genetic diversity, and can serve as a source population for reintroductions (Cypher 2010, Cypher and Van Horn Job 2012). Until recently this population appeared to be stable and may have even been expanding whereas most other San Joaquin kit fox populations are declining due to continuing habitat loss (USFWS 2020*a*). However, in March 2013, sarcoptic mange was detected among kit foxes in Bakersfield, and many of the cases were fatal (Cypher et al. 2017). The mite that causes mange, *Sarcoptes scabiei*, can infest various species including coyotes (*Canis latrans*), red fox (*V. vulpes*), and domestic dogs (*Canis lupus familiaris*) (Pence and Ueckermann 2002), and mange in kit foxes likely resulted from a "spillover" event from one of these species (Rudd et al. 2020*b*). Among red foxes, outbreaks of mange have caused catastrophic population declines of 50-98% and some of those populations have not subsequently recovered (Morner 1992, Soulsbury et al.

2007). Such severe population reductions or local extirpation could significantly imperil the San Joaquin kit fox.

After the first case detection in 2013, the disease spread rapidly throughout the Bakersfield kit fox population (Cypher et al. 2017). As of August 2023, at least 454 cases of mange in kit foxes have been documented, including at least 90 confirmed deaths. These numbers are just a fraction of the animals contracting mange and dying as many cases and fatalities went undetected. Evidence to date indicates that kit foxes are unable to recover from mange without treatment, and they do not appear to develop any immunity to the disease (Cypher et al. 2017). In the absence of any mitigation efforts, a significant population decline is likely. Indeed, from 2015 to 2019, kit fox detection rates at camera stations distributed across Bakersfield declined from 64.8% to 20.9% (CSUS ESRP unpublished data) indicating a marked reduction in kit fox abundance. In early 2019, a kit fox with mange was detected in the town of Taft located approximately 50 km west of Bakersfield. The origin of mange in Taft foxes is unknown. Since the first detection, at least 56 cases of mange in kit foxes have been documented, including seven fatalities. Again, these are undoubtedly underestimates of the actual cases and fatalities.

Since mange was first detected in the Bakersfield kit fox population, California State University-Stanislaus, Endangered Species Recovery Program (ESRP) staff began attempting to trap and treat foxes. California Department of Fish and Wildlife staff, the California Living Museum, and various volunteers have assisted with these efforts. For captured foxes with mild cases of mange, treatment consists of administering a dose of Revolution® (active ingredient, selamectin) and immediate release. Selamectin kills the mites that cause mange. Foxes with more severe cases of mange are taken to the California Living Museum for treatment, which commonly consists of biweekly doses of selamectin, administering fluids for dehydration, and antibiotics for secondary infections. Upon recovery, the foxes are released again, usually with a Seresto® anti-mite collar (active ingredient, flumetherin) that helps to prevent reinfection for 3-5 months. Similar efforts were initiated in Taft in 2019.

In addition to efforts to treat foxes, several studies have been conducted to collect information on epidemiological attributes of mange in kit foxes. These have included population monitoring (Deatherage et al. 2021), investigating the genomics of mange mites to try to identify their origin (Rudd et al. 2020*b*), assessing the efficacy of acaricidal collars in preventing mite infections (Rudd et al. 2020*a*), and modeling potential kit fox population effects from mange (Foley et al. 2023). Of particular interest is the process by which mange is being transmitted between individual foxes. Generally, contact between individuals is necessary for transmission of the mites that cause mange. Physical contact commonly occurs among individuals in a social unit, but rarely between individuals of different groups. Despite this, mange spread rapidly throughout both the Bakersfield and Taft kit fox populations.

Kit foxes are obligate den users and use a den every day of the year (Cypher 2003). In an earlier effort to model mange transmission dynamics, Montecino-Latorre et al. (2019) concluded that den sharing among kit foxes likely was a significant factor in the intraspecific transmission of mange among kit foxes. In this study, it was assumed that mite transmission was by foxes coming into contact within the dens. However, Arlian et al. (1989) determined that mange mites could survive for some period of time off-host if conditions (particularly temperature and humidity) were appropriate. Loredo et al. (2020)

measured climatic conditions within kit fox dens and then applied criteria from Arlian et al. (1989) to the results to estimate how long mites might be able to survive off-host in the dens. They reported that mites might be able to survive in the soil of the dens for a mean time of 2.0 days in summer, 7.4 days in winter, and 4.8 days overall. These results indicate that if a kit fox with mange uses a den, then another fox potentially can become infested with mange mites by using the same den even if the den is not used simultaneously by the two foxes. Use of common dens could be a mode of mite transmission that facilitates the rapid spread of mange among kit foxes, particularly in urban environments where survival rates, reproductive rates, and consequently densities are relatively high (Cypher 2010, Cypher et al. 2023*b*) resulting in greater use of common dens.

We investigated den use patterns by urban San Joaquin kit foxes in Bakersfield, CA. We tracked radio-collared foxes to dens and then monitored those dens with field cameras to determine the number of additional foxes that used each den during durations when mange mites potentially would survive in the soil within dens. Our objectives were to determine (1) the number of additional foxes that potentially could become infested with mites by using a den that was used by a fox with mange, and (2) the number of dens that a given fox with mange could potentially contaminate before it died from mange. An additional aspect of this project was to capture and treat kit foxes with mange whenever possible.

STUDY DESIGN

Study area

This project was conducted on the California State University-Bakersfield (CSUB) campus in Bakersfield, California (Fig. 1). The campus is approximately 152 ha (375 ac) in size. It is surrounded by urban land uses consisting primarily of commercial and residential developments. Irrigated lawns and landscaping are present around buildings and on athletic fields. However, large portions of the campus are unirrigated and covered by dense growth of ruderal plants, particularly non-native species such as red brome (*Bromus madritensis*), wild barley (*Hordeum murinum*), black mustard (*Brassica nigra*), and puncture vine (*Tribulus terrestris*). These plants are green in the winter and early spring and dry the rest of the year.

San Joaquin kit foxes are abundant on the campus and in 2022-23 when data were collected for this study, the number using the campus was estimated to be approximately 3-4 dozen animals. San Joaquin kit foxes commonly use the entire campus, particularly at night when they are primarily active. Kit foxes with mange have relatively regularly been detected on the campus since the beginning of the epidemic in Bakersfield. Over the years, numerous kit fox dens have been located on the campus by maintenance staff and researchers (e.g., Westall et al. 2019, Loredo et al. 2020).

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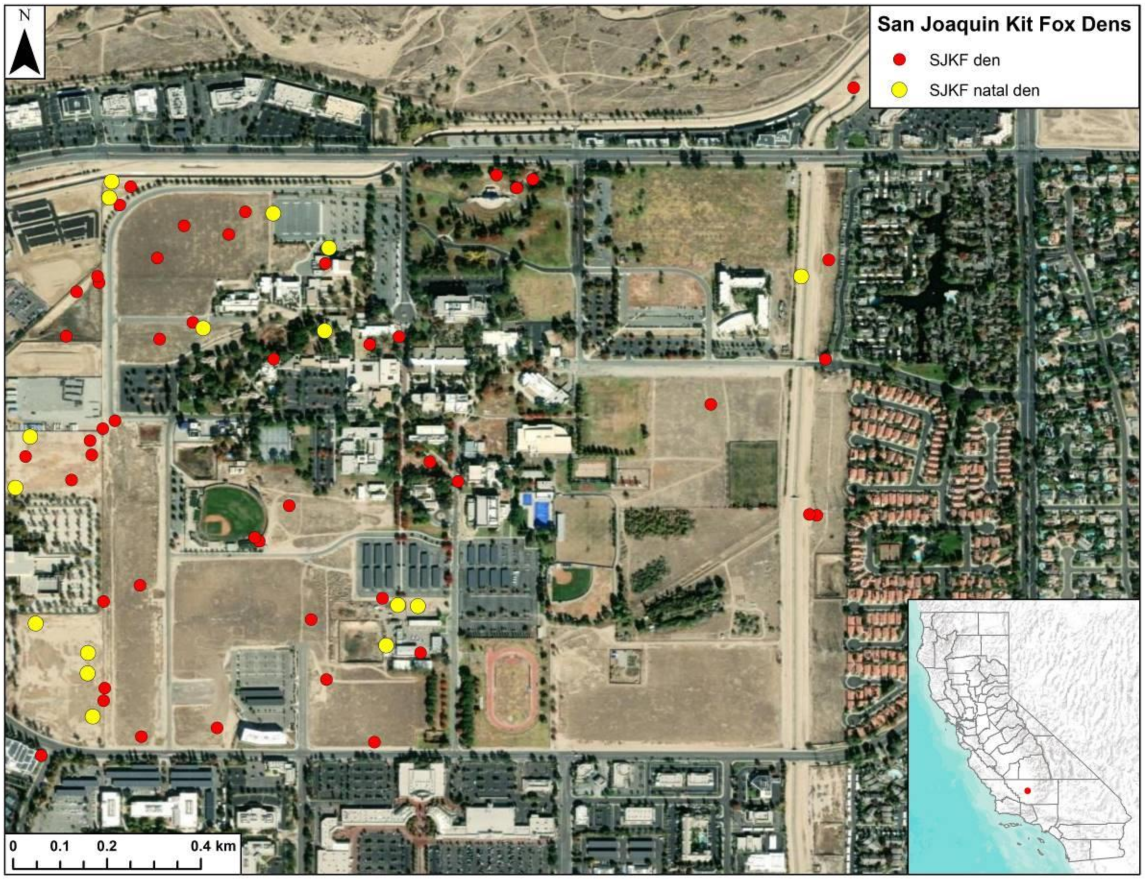

Figure 1. Campus of the California State University-Bakersfield in Bakersfield California and locations of dens used by radio-collared San Joaquin kit foxes during June 2022-April 2023.

Kit fox live-trapping and radio-collaring

Live-trapping for kit foxes was initiated in June 2022. Additional trapping efforts were conducted as needed when kit foxes with mange were detected and also in late fall 2022 to collar additional foxes, particularly young-of-the-year that were too light in weight prior to this to wear a radio-collar. Kit foxes were captured using wire-mesh live-traps (38 x 38 x 107 cm) baited with a protein item (e.g., hot dogs, canned cat food, hardboiled eggs) and covered with tarps to provide protection from inclement weather, sun, and irrigation sprinklers. Traps were set in late afternoon or early evening and then checked beginning around sunrise the next morning. Captured kit foxes were coaxed from the trap into a denim bag and handled without chemical restraint. Data collected for each fox included date, location, sex, age (adult or juvenile), mass, and dental condition, and a uniquely numbered tag was placed in one ear. Also, a non-toxic permanent hair dye (Nyanzol-D; Albinal Dyestuff, Inc., Jersey City, New Jersey) was used to create a unique symbol on both sides of each fox so that it could be identified in images collected by field cameras.

Foxes that were sufficiently large (i.e., females > 2 kg, males > 2.4 kg) were fitted with collars (Quantum 4000E Micro Mini Collars, Telemetry Solutions, Concord, CA) equipped with a GPS tracking unit and a VHF transmitter with a mortality sensor. The GPS units were programmed to collect four locations per night at varied times each night. Each unit included a UHF download function so that data could be downloaded remotely using a base station (4000ER Base Station, Telemetry Solutions, Concord, CA). All foxes were released at the capture site. All fox trapping, handling, and collaring were consistent with guidelines for the use of wild animals in research established by the American Society of Mammalogists (Sikes et al. 2011), and conducted in accordance with conditions and protocols established in the research permit (TE825573-6) held by California State University at Stanislaus-Endangered Species Recovery Program from the U.S. Fish and Wildlife Service and a Memorandum of Understanding from the California Department of Fish and Wildlife.

Kit fox and den monitoring

Once each week, we attempted to locate the VHF signal of each radio-collared fox using a telemetry receiver (Model R1000, Communications Specialists, Inc., Orange, CA). Telemetry signals initially were detected using an omni-directional antenna (Model RA-5A; Telonics, Mesa, AZ) magnetically mounted on the roof of a vehicle. Once a signal was detected, a 3-element handheld Yagi antenna (Model RA-150, Communications Specialists, Inc., Orange, CA) was used to navigate to the location of a given fox, which typically was a den. Each new den was assigned a unique number and its coordinates were recorded on a cell phone using the AmigoCloud application (AmigoCloud, Seattle, WA). We also attempted to download location data from the collars each week.

Use of each den by kit foxes was monitored using an automated camera station. We used Cuddeback Digital Black Flash IR cameras that employ a “black flash” infrared LED flash that creates almost no light visible to humans and that also take high-resolution images (20 megapixels). The black flash causes less disturbance to animals and the lack of a bright flash significantly reduces the potential to alert people to the presence and location of the camera, and therefore reduces the potential for vandalism or theft of the camera station or disturbance to the den. The camera stations were operated at each den for seven nights, which was the mean maximum estimated time that mange mites might survive off-host in a den (Loredo et al. 2020).

Data summary and analysis

At the end of each week-long monitoring session at a given den, images were downloaded from each camera and reviewed. We estimated the number of additional foxes that might become infested with mites if the fox originally tracked to the den had mange. For each of the week-long monitoring sessions at each den, the number of individual foxes that used the den other than the fox originally tracked to the den was determined for the first two nights, first four nights, and finally all seven nights that the camera was operated. The numbers of nights corresponded to the mean estimated time that mites might survive off-host in the den in summer, across all seasons, and winter, respectively (Loredo et al. 2020). We also estimated the number of foxes that were known to be in the den concurrently with the original fox tracked to that den. This provided an estimate of the number of foxes that potentially could have been infested with mites through direct contact if the original fox had mange.

Seasons were defined as summer (June-September), fall (October-November), winter (December-January), and spring (February-April). The summer months corresponded to the pup dispersal period, fall corresponded to the pairing period, winter corresponded to the breeding period, and spring corresponded to the pup-rearing period.

For the two-day, four-day, and seven-day intervals, we determined the frequency of monitoring sessions in which other foxes were detected using a den to which a radio-collared fox had been tracked. We used contingency table analysis and a Pearson chi-square test to compare frequencies among seasons and between sexes. For each of the time intervals, we used the General Linear Models function in SPSS (SPSS Statistics package, ver. 29.0.1.1; IBM, Armonk, New York, USA) to conduct a two-way analysis of variance to compare the mean number of other foxes detected using a den to which a radio-collared fox had been tracked as well as the mean number of foxes that were known to be in the den concurrently with the radio-collared fox. For these analyses, the model included season and sex as fixed factors and a sex*season interaction term. Means were compared among seasons using a Least Significant Difference multiple comparison test. For the spring season, we determined which of the radio-collared foxes were associated with a litter of pups either as the mother, father, or a helper. For each of the three time intervals, we then compared the mean number of other foxes detected using a den to which a radio-collared fox had been tracked using *t*-tests.

Kit foxes that contract mange typically die within 4-5 months if they are not treated (Cypher et al. 2017). We conservatively used 120 days as the period between disease onset and death. For each radio-collared fox that was monitored for at least 120 days, we determined the number of times that the fox was detected by radio-telemetry or camera station, the number of unique dens used by that fox, the number of other kit foxes using a den to which the radio-collared kit fox had been tracked, and the number of other kit foxes that were detected using a den concurrently with the radio-collared. These numbers were tallied for each fox for 120 days beginning when it was first tracked to a den. A two-way analysis of variance was used to compare the mean numbers among seasons and between sexes, and to identify any interactions between these two variables.

To examine spatial overlap among the radio-collared foxes, we used the location data from the GPS collars to calculate home ranges for each fox. We used the extension Home Range Tools (ver. 2.0, Centre for Northern Forest Ecosystem Research, Thunder Bay, Ontario, Canada) for ArcMAP (ver. 10.6, ESRI, Redlands, CA). The home range for each radio-collared fox was estimated by calculating a 95% Minimum Convex Polygon (MCP). We used 95% MCPs for home ranges to avoid inclusion of long-distance exploratory movements that would artificially inflate home range size and therefore would not be representative of the area used by foxes to satisfy life-history requirements.

For all statistical analyses, we set α at 0.10. We chose a more relaxed α value to reduce the risk of committing a Type II error, which tends to be high with small sample sizes like those in this study (Alldredge and Ratti 1986). Detecting trends with ecological data can be challenging because all potential confounding factors cannot be controlled (Germano et al. 2012). By reducing the Type II error rate, we were more likely to detect potential relationships that can be further investigated (Rotenberry and Wiens 1985, Taylor and Gerrodette 1993, Steidl et al. 1997, Di Stefano 2003, Scherer and Tracey 2011).

Treatment of kit foxes for mange

We identified kit foxes with sarcoptic mange from trapping for research projects, field camera stations, reports from other biologists, or reports from the public. We attempted to capture any foxes with mange and treat them. Captured foxes without obvious signs or with mild cases were treated with a dose of selamectin (Revolution, Zoetis, Kalamazoo, MI) at a rate of 6 mg/kg body weight. The dose was administered with a needleless syringe directly on the skin on the dorsal surface of the head. Treated foxes then were released at the capture site. Selamectin is a topical acaricide that kills ectoparasites including the mites that cause mange. Foxes with more severe cases of mange were transported to the California Living Museum in northeast Bakersfield for a 4-6 week treatment regime consisting of biweekly doses of Revolution, fluids for dehydration, antibiotics for secondary infections, and any other required support. Upon recovery, the foxes were released again, usually with a long-acting Seresto acaricidal band (Bayer HealthCare, Shawnee Mission, KS) embedded in a neoprene collar. These bands help to prevent reinfection for 3-5 months. Automated cameras commonly were operated for multiple nights (typically 3-10) in areas where trapping was conducted to determine whether additional untrapped foxes were still present. If so, then additional trapping was conducted to capture and treat more individuals. Trapping also was occasionally repeated after 2-3 weeks in areas where foxes were treated in order to administer a second dose of selamectin.

RESULTS

During the study, 37 kit foxes were captured. Radio-collars were placed on 20 (10 males, 10 females) of the foxes; 16 in summer 2022 and 4 in winter 2022-23. All of the captured foxes were dye-marked to facilitate identification on field cameras. Collared kit foxes were tracked to 68 different dens during 44 weeks of monitoring (24 June 2022-28 April 2023), and 390 7-day monitoring sessions were conducted at these dens.

The proportion of weeks in which another fox used a den to which a collared fox was tracked was 78.5% for the first two nights, 84.4% for the first 4 nights, and 89.0% for the full seven-night session. Within these intervals (Table 1), the proportion did not vary among seasons (2 nights: $\chi^2 = 2.28$, 3 df, $p = 0.516$; 4 nights: $\chi^2 = 0.94$, 3 df, $p = 0.816$; 7 nights: $\chi^2 = 2.05$, 3 df, $p = 0.562$) or between sexes (2 nights: $\chi^2 = 1.99$, 1 df, $p = 0.158$; 4 nights: $\chi^2 = 1.28$, 1 df, $p = 0.258$; 7 nights: $\chi^2 = 0.81$, 1 df, $p = 0.368$).

The mean number of other kit foxes using a den within the first two nights, four nights, and seven nights after a radio-collared fox was tracked to the den was 1.83, 2.22, and 2.52, respectively (Table 2). The mean number did not vary among factors for the two-night interval, but did vary between sexes for the four-night and seven-night intervals with the means for females being consistently higher than those for males. The means varied among seasons for the seven-night interval and was highest in fall and lowest in spring (Table 3). The sex*season interaction was significant for the four-night and seven-night intervals with the means for females commonly being higher than those for males in summer, fall, and spring, but lower than those for males in winter (Figs. 2-4). The model for the mean number of foxes found in a den concurrently with the tracked fox was significant (Table 3) with means for females being higher than those for males and means for winter and spring being higher than those for summer and fall (Table 2). The sex*season interaction also was significant with the means for females commonly being higher than those for males in summer, fall, and spring, but lower than those for males in winter (Figs. 5).

Table 1. Proportion of monitoring sessions that another kit fox used a den to which a radio-collared kit fox had been tracked in the first two nights, first four nights, and all 7 nights of a monitoring session, June 2022-April 2023 in Bakersfield, California.

		Proportion of sessions (%)		
	n	**2 nights**	**4 nights**	**7 nights**
Total	390	78.5	84.4	89.0
Season:				
Summer	99	73.7	81.8	85.9
Fall	68	82.4	83.8	92.6
Winter	104	77.9	84.6	88.5
Spring	119	80.7	86.6	89.9
Sex:				
Female	264	80.7	86.0	90.2
Male	126	73.8	81.0	86.5

Table 2. Mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked in the first two nights, first four nights, and all 7 nights of a monitoring session and the mean number of other foxes during the session documented inside the den concurrently with the tracked fox, June 2022-April 2023 in Bakersfield, California. In each column, seasonal means with the same letter were not significantly different.

		2 nights		4 nights		7 nights		Foxes in den concurrently	
	n	**Mean (SE)**	**Max**	**Mean (SE)**	**Max**	**Mean (SE)**	**Max**	**Mean (SE)**	**Max**
Total	390	1.83 (0.07)	8	2.22 (0.08)	9	2.52 (0.09)	12	1.77 (0.09)	12
Season:									
Summer	99	1.80 A (0.16)	6	2.11 A (0.16)	6	2.33 BC (0.17)	6	1.39 B (0.17)	6
Fall	68	1.96 A (0.17)	6	2.50 A (0.21)	6	3.06 A (0.20)	7	1.74 B (0.21)	5
Winter	104	2.00 A (0.17)	8	2.34 A (0.19)	9	2.63 AB (0.21)	12	1.99 A (0.21)	12
Spring	119	1.62 A (0.10)	4	2.03 A (0.11)	4	2.28 C (0.11)	4	1.92 AB (0.12)	4
Sex:									
Female	264	1.89 (0.08)	8	2.30 (0.09)	9	2.61 (0.10)	12	1.92 (0.10)	10
Male	126	1.70 (0.14)	8	2.03 (0.15)	9	2.34 (0.17)	12	1.46 (0.17)	12

Table 3. Results of two-way analysis of variance for the mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked in the first two nights, first four nights, and all 7 nights of a monitoring session and the mean number of other foxes during the session documented inside the den concurrently with the tracked fox, June 2022-April 2023 in Bakersfield, California.

	F	df	p
2-night interval:			
Model	1.33	7,382	0.233
Sex	2.97	1,382	0.085
Season	1.20	3,382	0.310
Sex*Season	0.81	3,382	0.489
4-night interval:			
Model	2.08	7,382	0.045
Sex	4.21	1,382	0.041
Season	1.06	3,382	0.367
Sex*Season	2.23	3,382	0.085
7-night interval:			
Model	2.95	7,382	0.005
Sex	3.79	1,382	0.052
Season	2.55	3,382	0.055
Sex*Season	2.25	3,382	0.083
Foxes in den concurrently:			
Model	3.72	7,382	<0.001
Sex	8.91	1,382	0.003
Season	2.81	3,382	0.039
Sex*Season	4.53	3,382	0.004

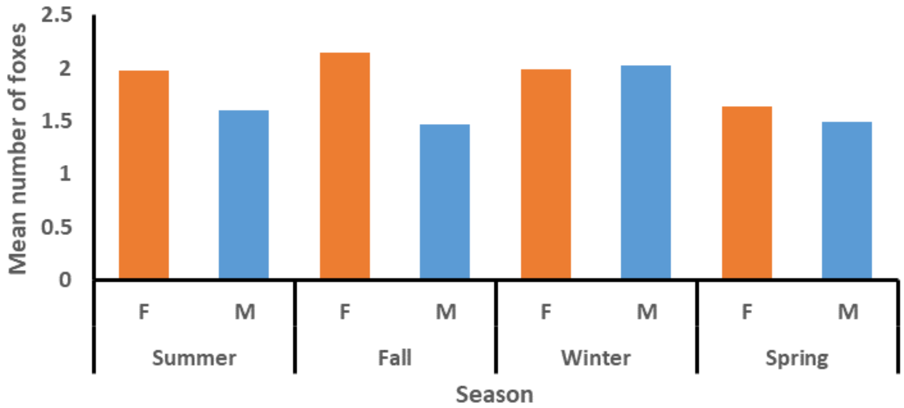

Figure 2. Mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked in the first two nights by season and sex, June 2022-April 2023 in Bakersfield, California.

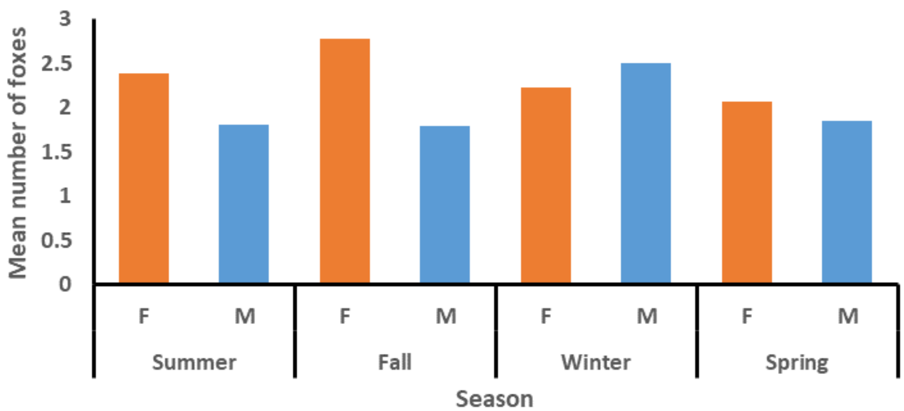

Figure 3. Mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked in the first four nights by season and sex, June 2022-April 2023 in Bakersfield, California.

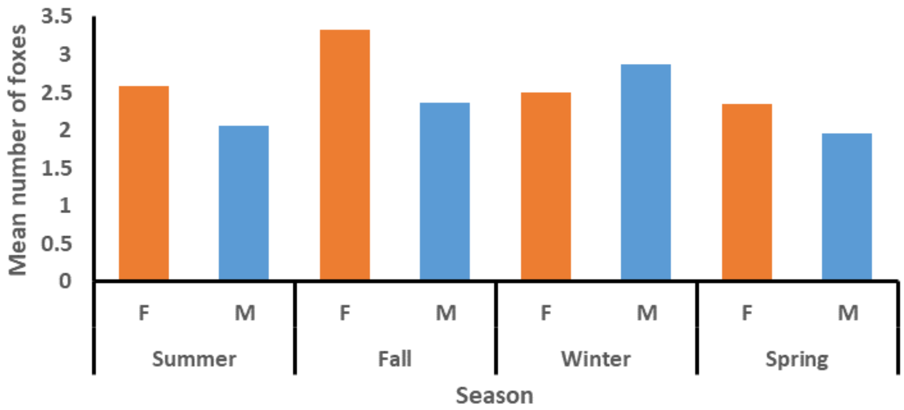

Figure 4. Mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked in the first seven nights by season and sex, June 2022-April 2023 in Bakersfield, California.

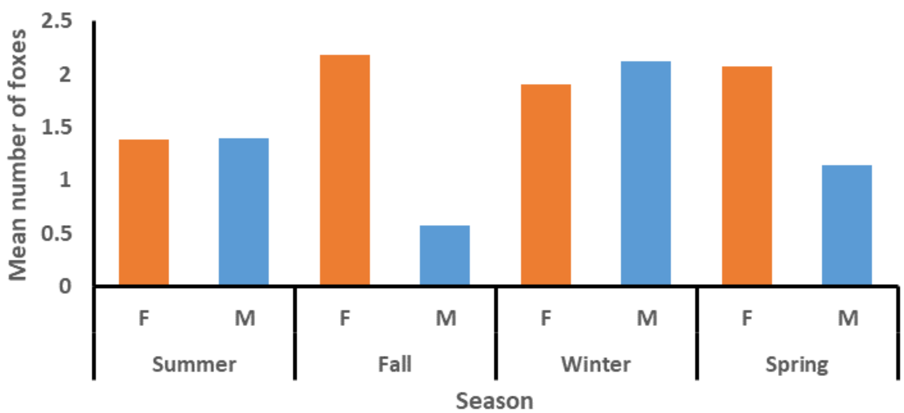

Figure 5. Mean number of other kit foxes documented inside a den concurrently with the tracked kit fox during a week-long monitoring session by season and sex, June 2022-April 2023 in Bakersfield, California.

The mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked usually was lowest in spring. This may have been due to foxes that reproduced limiting use of dens with young pups. Indeed, the mean number was higher for foxes not associated with pups compared to foxes associated with pups with the differences being significant for the four-night and seven-night intervals (Table 4).

Table 4. Comparison of the mean number of other kit foxes using a den to which a radio-collared kit fox had been tracked in the first two nights, first four nights, and all 7 nights of a monitoring session for reproducing and non-reproducing foxes in spring 2023 in Bakersfield, California.

	Mean (SE)		
	Reproducing (n = 102)	**Non-reproducing (n = 17)**	$t_{1,117}$ p
2-night interval	1.56 (0.10)	2.0 (0.26)	2.57 0.112
4-night interval	1.94 (0.12)	2.59 (0.29)	4.31 0.040
7-night interval	2.19 (0.12)	2.82 (0.29)	4.07 0.046

Seventeen radio-collared kit foxes were tracked for full 120-day intervals with some of the foxes being tracked for intervals in each of two seasons: summer-fall and winter-spring. The mean number of detections via radio-telemetry or field camera during these intervals was for all foxes and seasons was 21.6 (Table 5). The mean number of dens used was 7.6 (Table 5) with no significant sex or season effects ($F_{3,27}$ = 1.33, p = 0.286). The mean number of other foxes detected during an interval that used a den in the same week that the collared fox was detected using the den was 9.8 (Table 5) with no significant sex or season effects ($F_{3,27}$ = 1.84, p = 0.163). The mean number of other foxes that were in the den concurrently with the collared fox was 7.3 (Table 5) with no significant sex or season effects ($F_{3,27}$ = 2.21, p = 0.110).

We collected 13,945 GPS locations on 19 radio-collared kit foxes and sufficient locations were available to estimate home ranges for 19 foxes. The locations (Fig. 6) and the home ranges (Fig. 7) indicated extensive spatial overlap among the foxes on the study site. We did not attempt to calculate overlap indices between home ranges given the obvious extent of overlap.

Table 5. Season and sex comparison of the mean number of detections, dens used by radio-collared kit foxes, other kit foxes using a den to which a radio-collared kit fox had been tracked, and other kit foxes using a den concurrently with a radio-collared fox within 120 days of a radio-collared fox being tracked to a den during, June 2022-April 2023 in Bakersfield, California.

	Season		Sex		
	Summer-fall	**Winter-spring**	**Female**	**Male**	**Total**
n	16	15	18	13	31
Detections					
Mean (SE)	13.3 (1.5)	30.5 (2.7)	23.3 (2.4)	19.3 (4.0)	21.6 (2.2)
Range	6-30	8-59	8-36	6-59	6-59
Dens used					
Mean (SE)	6.7 (0.5)	8.5 (1.0)	7.5 (0.6)	7.6 (1.0)	7.6 (0.5)
Range	4-10	2-15	3-11	2-15	2-15
Other foxes same week					
Mean (SE)	9.4 (0.9)	10.2 (1.2)	9.5 (0.9)	10.2 (1.3)	9.8 (0.8)
Range	4-16	4-21	4-16	4-21	4-21
Other foxes concurrently					
Mean (SE)	7.1 (0.8)	7.5 (1.0)	6.9 (0.7)	7.8 (1.2)	7.3 (0.6)
Range	2-14	2-17	2-14	2-17	2-17

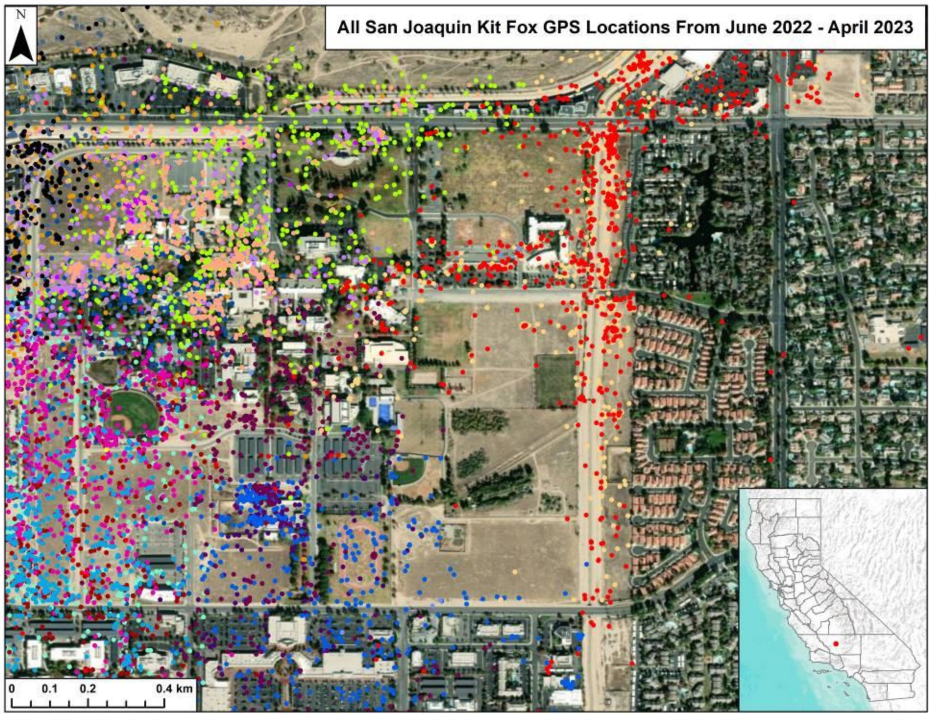

Figure 6. GPS locations for 19 kit foxes, June 2022-April 2023 in Bakersfield, California. Each color represents a different fox.

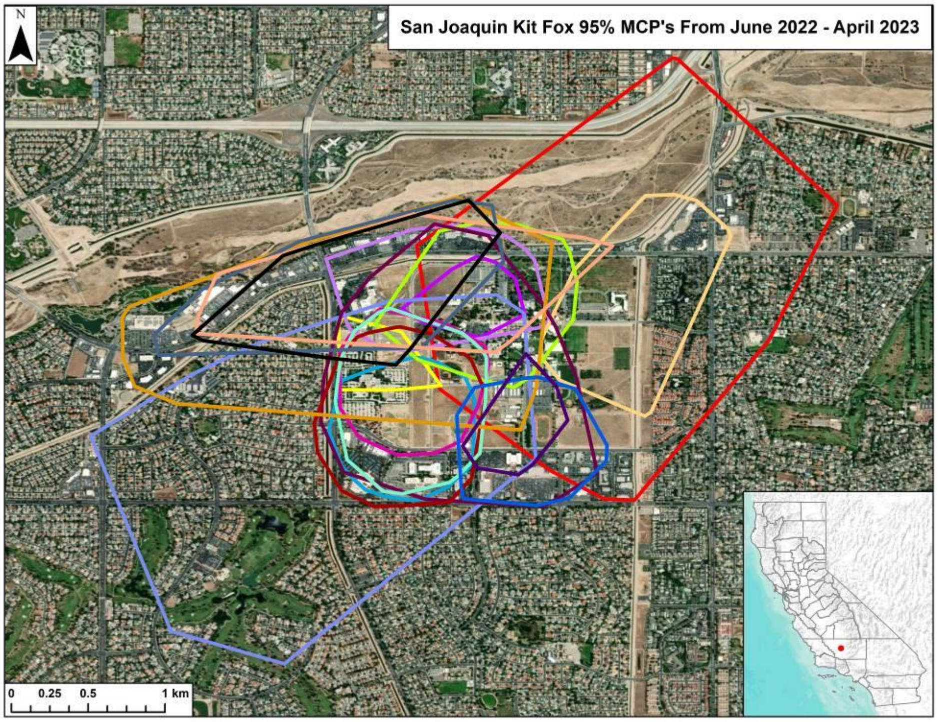

Figure 7. Home ranges (95% Minimum Convex Polygons) for 18 kit foxes, June 2022-April 2023 in Bakersfield, California. One fox with a particularly large home range is not displayed.

During this project, we captured and treated 87 kit foxes; 36 exhibited signs of mange (29 in Bakersfield, 7 in Taft) and 66 did not exhibit signs (58 in Bakersfield, 8 in Taft) but were treated prophylactically. (Fifteen foxes were captured twice: once with mange and then later without mange.) Of the foxes with mange, nine of the cases (8 in Bakersfield, 1 in Taft) were sufficiently severe that the foxes were taken to the California Living Museum for treatment and rehabilitation. One fox died of complications from advanced mange, but all the others foxes survived and were eventually released at their capture location.

DISCUSSION

On our study site in the urban environment of Bakersfield, we found that use of a given den by multiple kit foxes occurred quite frequently. Of significance, use of a den by other foxes commonly occurred within intervals of time during which live mange mites potentially could be present in the soil of the den following use by a fox with mange. Furthermore, two or more foxes frequently were documented in a den concurrently indicating a high potential for direct contact and mite transmission. As many as 12 foxes were detected sharing a den concurrently with a given monitored fox during a seven-day period. Sharing of dens, burrows, or resting sites is suspected in the transmission of mange among bare-nosed wombats (*Vombatus ursinus*; Skerratt et al. 1998) as well as a suite of sympatric carnivores inhabiting the Białowieza Forest in Poland (Kołodziej-Sobocińska et al. 2014).

These observed den use patterns significantly enhance the potential for mange transmission between individual kit foxes. Furthermore, the potential for transmission of other diseases such as rabies, canine distemper, parvovirus, canine adenovirus, and other parasites is enhanced as well. The observed high rate of den sharing may have contributed to the rapid spread of mange throughout the urban kit fox population in Bakersfield following the first case detection in spring 2013 (Cypher et al. 2017, Foley et al. 2023). The ability to move long distances in the urban environment may have contributed as well. Kit foxes have been documented moving 13 km (straight-line distance) in Bakersfield (Foley et al. 2023, CSUS ESRP unpublished data).

We caution that all of the estimates of den sharing should be considered conservative. For a variety of reasons, den sharing likely was even higher than we observed. Occasionally, we were unable to locate a radio-collared fox resulting in gaps in the data set for that fox of one or more weeks during which any den sharing with other foxes was not recorded. We also occasionally observed unmarked foxes on the cameras and it was not always clear whether we were observing a single or multiple unmarked foxes. When uncertain, only one fox was tallied. The cameras did not always detect all of the foxes using a particular den. We base this on the fact that on occasion, radio-collared foxes were tracked to a den where a camera station was then established, but the collared fox was not detected leaving or using the den. This could have been a result of the foxes moving faster than the trigger speed of the cameras. Very commonly, a radio-collared fox was tracked to a den but was not documented using that den every day. The camera may have missed detecting the fox, as mentioned above. However, in many cases the fox could have been using another den where den sharing was not being monitored. Indeed, on numerous occasions, foxes originally tracked to one den were also detected using other dens that also were being monitored during the same week. Thus, the actual rates of den sharing very likely were higher than the rates we documented.

In general, kit fox den use patterns did not differ significantly among seasons, although den sharing trended somewhat higher in fall and winter. This may have been due to lower temperatures during these seasons and possible huddling behavior by foxes to conserve body heat. Increased den sharing during these seasons also was observed among kit foxes in natural habitat (Koopman et al. 1998) and among swift foxes (*Vulpes velox*), a species closely related to kit foxes (Kitchen et al. 2005). During the period of gestation and pup-rearing, foxes that were parents to a litter of pups or that functioned as a helper in raising their parents' pups shared dens less than foxes that were not associated with a litter. To protect their litter, foxes likely avoid or limit interactions with the pups by foxes other than the mother, father, and any helpers. At a natural lands study site, reproducing foxes also exhibited significantly lower den sharing during February when new litters were being born (Koopman et al. 1998).

A sex bias in den sharing was apparent with females consistently sharing more frequently than males. This trend also was observed in a natural environment with offspring from current as well as previous litters commonly sharing dens with their mother (Koopman et al. 1998). We were not sure of most relationships between monitored foxes and therefore could not determine whether related foxes were the ones frequently denning with adult females. Regardless, these results suggest that females may play a larger role in the spread of mange compared to males. That said, the frequency of den sharing by the males was likely sufficient to facilitate the spread of mange.

During a hypothetical period (120 days) during which a given kit fox could be shedding mites prior to succumbing to mange, each monitored fox used over seven dens on average with some foxes using as many as 15 dens. During this same hypothetical period, almost 10 other foxes on average and as many as 21 foxes used the same den within one week of the den being used by the monitored fox. Finally, over seven other foxes on average and as many as 17 foxes were found using the den concurrently with the monitored fox. The observed use of multiple dens and the sharing of dens either separately or concurrently during the hypothetical period all create abundant opportunity for a fox without mange to use a contaminated den or to come in contact with an infected fox and contract mange. Also, we emphasize that the 120-day period provides a conservative estimate of dens used and den sharing. Based on our efforts to monitor and capture and treat foxes, a number of foxes with mange lived longer than the 120-day period before succumbing.

Disease spread and transmission depends on the number of contacts between individuals, the probability that an infected individual will transmit the disease to a susceptible individual, and the duration of infectiousness. With regards to the kit fox population in our study, the mean number of foxes that shared a den concurrently with a monitored fox was 7.3 other foxes. Intuitively, diseases are most easily spread when infectious individuals maintain prolonged contact with susceptible individuals and having contacting with 7 or more individuals at any given time may help explain the observed rapid spread of mange among Bakersfield foxes to epidemic proportions that eventually resulted in a population decline.

Importantly, a significant epidemiological metric for how infectious a disease may be is the basic reproduction ratio, R_0 (Delamater et al. 2019). R_0 is the average number of susceptible individuals that can be infected by a single diseased individual. It is a determining factor in whether an epidemic continues ($R_0 > 1$) or terminates ($R_0 < 1$). A number of factors affect this value and it can vary temporally and spatially.

To terminate a disease epidemic, the overarching goal of intervention strategies, either stated or implied, is to reduce R_0 to less than 1 (Blancou et al. 2009). Strategies to achieve this include vaccination (e.g., against rabies and classical swine fever; MacInnes 1987, Blancou et al. 2009), population reduction (e.g., culling, fertility control; Carter et al. 2009), and treating individuals. The first two strategies are not available for San Joaquin kit foxes. No vaccine is available for mange. Population reduction is challenging logistically and ethically and commonly is unpopular with the public (Carter et al. 2009, Miguel et al. 2020). These challenges are enhanced substantially when an endangered species is involved (Breed et al. 2009). We did attempt to treat individuals with topical selamectin doses and flumethrin collars, but the former only protects foxes for 2-4 weeks and the latter for 3-5 months (Rudd et al. 2020*a*). After these periods, the foxes again become susceptible to infection with mange mites. Indeed, we treated a number of foxes that had second and even third mange infections. Thus, a number of individual kit foxes were saved but the population implications of these efforts are uncertain. A R_0 value of less than 1 also might be achieved naturally through mortalities as an epidemic rages through a population. Indeed, this may have been observed in the Bakersfield kit fox population as the population declined and the number of foxes with mange abated (Fig. 8).

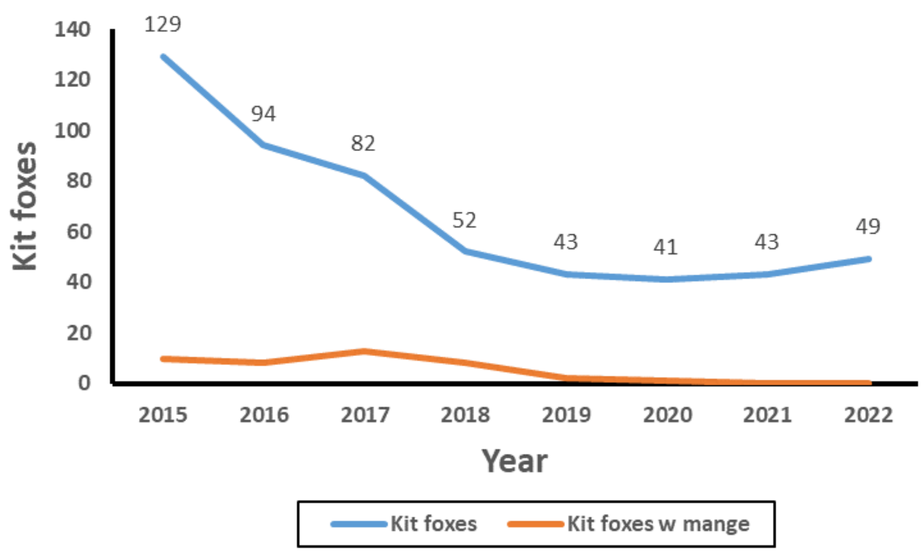

Figure 8. Total number of kit foxes and kit foxes with mange detected during camera station surveys in Bakersfield, California during 2015-2022 (CSUS ESRP unpublished data).

Mange has not been detected among kit foxes in natural habitats, even those adjacent to the Bakersfield urban environment (Cypher et al. 2023*a*). Foxes, including some with mange, routinely cross the interface between urban and natural lands (Cypher et al. 2023*a*). Kit foxes in natural habitats commonly use multiple dens during the course of a year with mean (range) estimates per fox including 8.4 (1-31; Cypher et al. 2019), 11.8 (range = 1-16; Koopman et al. 1998), 13.0 (3-23; Hall 1983), 15.6 (9-25; L. Spiegel, California Energy Commission, unpubl. data), 16.0 (1-58; Briden et al. 1992), 17.6 (1-64; Reese et al.

1992), and 19.4 (H.T. Harvey and Associates 2019). Den sharing also commonly occurs among kit foxes in natural habitats (Koopman et al. 1998, Ralls et al. 2001). This all suggests that the potential for mange to spread into and throughout kit fox populations in natural habitat should be high.

The social ecology of kit foxes may offer some explanation for the apparent absence of mange in natural populations. Foxes that share dens are almost always related (O'Farrell and Gilbertson 1986, Koopman et al. 1998, Ralls et al. 2001). Den sharing between individuals from different social groups is rare and apparently primarily occurs during pair formation when a male and a female from different social groups attempt to form a pair (Ralls et al. 2001). Otherwise, foxes from different social groups do not share dens. Even if foxes from adjacent family groups used a common den along the margin of their ranges, concurrent use is unlikely and an uninfected fox would need to use the den within a week of it being used by a fox with mange in order for the disease to spread between the groups.

In urban kit fox populations, high survival, high reproductive success, abundant resources, and fewer vacant home ranges for dispersing foxes to move into result in higher fox densities compared to populations in natural habitats (Cypher 2010, Cypher et al. 2023*b*). This results in extensive spatial overlap as was documented among the home range polygons of the monitored foxes on our study site (see Figs. 6 and 7). This overlap likely results in even greater den sharing including among social groups even if the shared dens are not used concurrently by members of different groups. Extensive spatial overlap and den sharing also was observed in a high-density population of bare-nosed wombats, a species also impacted by mange (Skerratt et al. 2004).

The patterns of den use by kit foxes observed in this study and the implications for mite transmission indicate that preventing the spread of sarcoptic mange in the urban population will be quite challenging. One possibility we had considered was some form of den treatment, similar to the strategy used to treat prairie dog (*Cynomys spp.*) burrows to kill the fleas that transmit plague (Tripp et al. 2017, 2022). However, just locating the multiple dens used by foxes would be difficult, and treating the den would not necessarily kill the mites on the foxes. Also, unless some sort of long-acting treatment that was safe for the kit foxes was available, a treated den could immediately be recontaminated by a fox with mange.

The den use patterns also highlighted the number of kit foxes that potentially could be infected by a single fox. Clearly, if a fox is detected with mange in a given area, the probability is high that a number of other foxes in the same area also are infected. This is consistent with our experiences in trapping for foxes with mange. In most instances, we have captured other foxes that also have mange. Consequently, we commonly trap for multiple nights, even once the fox that was originally detected has been captured. We then operate camera stations in the area for multiple nights (typically 3-10) in an effort to determine whether additional foxes with mange are present.

We will continue efforts to capture and treat any kit foxes detected with sarcoptic mange for as long as we have funding to do so. We also will continue efforts to identify strategies for treating foxes. Potential strategies that would be particularly beneficial include treatments that provide protection from mites for a longer period of time, and a treatment that could be administered orally thereby negating the need to capture foxes. We will explore alternative strategies to the extent we are able and also encourage others to do so as well.

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