Florida Key Deer Abundance and Recovery Following New World Screwworm Infestation

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Abstract - An infestation of *Cochliomyia hominivorax* (New World Screwworm, hereafter Screwworm) was detected in the endangered *Odocoileus virginianus clavium* (Florida Key Deer) population in July 2016. We assessed the impact of this infestation on Florida Key Deer population abundance and recovery potential. We synthesized historical mortality and population data with new analyses including monitoring of Florida Key Deer mortalities and estimation of abundance on Big Pine Key and No Name Key (islands that support 75% of the Florida Key Deer population). We documented 135 Screwworm-related Florida Key Deer mortalities (~9–20% of the total population) during the Screwworm outbreak (July 2016–January 2017). Most mortalities occurred in the adult male population, as Screwworm flies laid eggs on open wounds sustained from sparring during mating season. The Screwworm incident was contained prior to the 2017 fawning season, which prevented substantial negative impacts on females or fawns. Historical growth rates at similar population levels and sex ratios indicated that, absent other external variables (e.g., Hurricane Irma in September 2017), the population was likely to recover.

Introduction

The federally endangered *Odocoileus virginianus clavium* Barbour and Allen (Florida Key Deer, hereafter Key Deer) is the smallest sub-species of *Odocoileus virginianus* (Zimmermann) (White-tailed Deer) in North America and is endemic to the Florida Keys, which lie off the southern end of peninsular Florida (Hardin et al. 1984). Key Deer occupy a limited range, roughly from Little Pine Key in the east to Sugarloaf Key to the west (18–20 km linear distance; Fig. 1), and have maintained a relatively small extant population estimated to be <1500 Key Deer prior to the infestation by *Cochliomyia hominivorax* (Coquerel) (New World Screwworm, hereafter Screwworm) (Lopez et al. 2016, Villanova 2015). Approximately 75% of the population in 2016 resided on 2 adjacent islands, Big Pine and No Name keys, which comprise the core habitat for this species. Urban development has been a major concern in the recovery and management of Key Deer (Klimstra et al.

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1974, Lopez et al. 2004). In the past 30 years, the human population has increased nearly 10-fold on Big Pine and No Name keys (Folk 1991, Lopez 2001), resulting in changes to Key Deer sociobiology including larger group sizes, reduction in deer movements and changes in deer behavior (Hardin 1974; Folk1991; Folk and Klimstra 1991; Lopez et al. 2003, 2004). While supplemental feeding of Key Deer is prohibited by state (F.A.C. 39-27.002) and federal (16 U.S.C. 1531) laws (USFWS 1999), illegal feeding may be responsible for increased deer use of urban areas (Folk and Klimstra 1991, USFWS 1999), increased grouping of deer, and a "taming" or urbanization of Key Deer (Folk 1991, Folk and Klimstra 1991, Lopez et al. 2004).

In July 2016, several Key Deer were observed with lesions consistent with Screwworm infestation. Entomologists subsequently confirmed the presence of Screwworm in the Key Deer population. Adult male Key Deer are particularly vulnerable to Screwworm infestation due to sparring wounds sustained during the mating season (September–January). Similarly, females and fawns may be vulnerable during the fawning period (late spring) due to female birthing injuries and the fawns' umbilicus following birth. As a result, sustained presence of Screwworm in the Key Deer population through the fawning season could increase mortality and decrease population density, thereby hampering overall recovery efforts. Key Deer are highly visible and routinely observed by US Fish and Wildlife Service (USFWS) biologists and the general public, which facilitated effective detection and response efforts for infected Key Deer. Furthermore, Key Deer have an extensive monitoring and research history (e.g., Lopez 2001, Lopez et al. 1998, Parker et al. 2011, Silvy et al. 1975, Watts et al. 2008) that was drawn upon during the comprehensive response to management of the Screwworm infestation.

The Screwworm is native to the western hemisphere and is recognized as an important threat to livestock operations. The adult female Screwworm flies lay

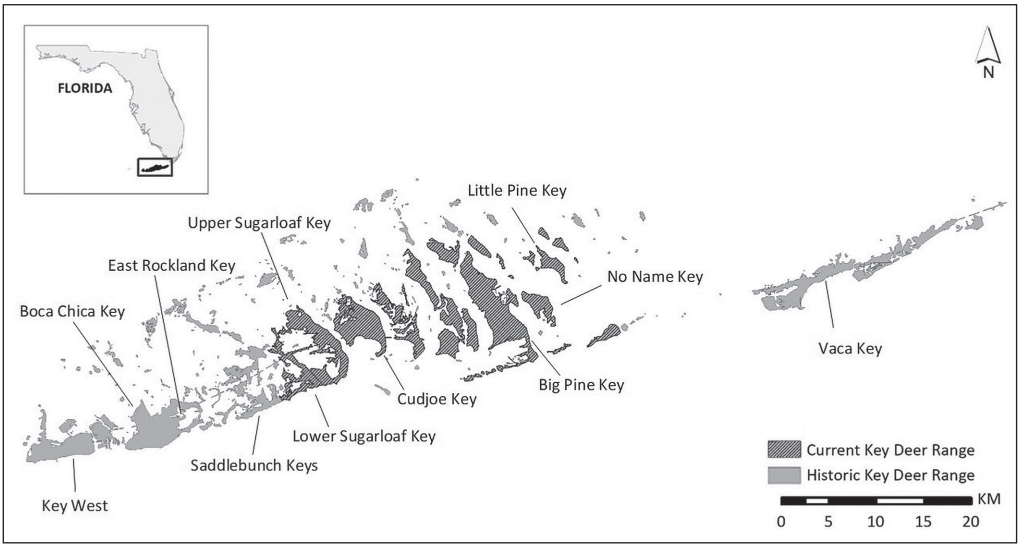

Figure 1. Historic and current ranges of the Florida Key Deer, Lower Florida Keys, 2017.

100–300 eggs at a time on the periphery of an open wound, orifice, or newborn umbilicus (Drees 2016), and up to 2800 eggs during their 10–30-day lifespan (CDFA 2016). The larvae emerge within 24 hours to feed upon the live and dead tissue within the wound (obligatory myiasis), causing large amounts of tissue loss, secondary infections, or toxicity, and resulting in death within 7–14 days. The magnitude of monetary and ecological effects from this threat was not realized until Screwworm flies reached the eastern United States in 1933 where they proceeded to severely impact livestock production (Wyss 2000). During this period, research into eradication and control focused primarily on the sterile insect technique (SIT; captive-reared irradiated males), The SIT was tested on the Island of Curaçao in 1954 and resulted in eradication of Screwworm from the island by the conclusion of testing (Baumhover et al. 1955). The SIT efforts were expanded to the southeastern and southwestern United States in the 1950s and 1960s, respectively. By 1966, the US was recognized as Screwworm free (Wyss 2000). Subsequent cooperative agreements between the US (US Department of Agriculture [USDA]) and additional countries such as Mexico, Guatemala, Belize, El Salvador, Honduras, and Panama extended control efforts south into Central America (Wyss 2000). As a result, the Screwworm is now primarily found in South American and Caribbean countries (CDFA 2016) and strict reporting and quarantine guidelines are followed in the US to minimize the risk of reintroduction.

The USDA has estimated that widespread reintroduction of Screwworm into the US would result in over $1 billion in losses to livestock operations alone (APHIS 2014). Additional ecological and monetary losses would likely exceed this estimate. In response to this threat to agricultural and ecological health, the USFWS, USDA, Florida Fish and Wildlife Conservation Commission (FWC), Florida Department of Agriculture and Consumer Services, Monroe County (FL), Texas A&M Natural Resources Institute, and local community members partnered together to address the Key Deer Screwworm infestation. This multi-agency response consisted of 3 distinct, but related actions: (1) elimination of New World Screwworm flies through sterile fly releases, (2) treatment of impacted and vulnerable animals through direct and indirect application of de-worming agents, and (3) determination of impact upon the Key Deer population.

The goals of our study related to action 3 as we assessed the status of the Key Deer population and determined potential impacts of the Screwworm infestation. Our specific objectives were: (1) determine population density using distance-sampling surveys in the Key Deer core habitat (i.e., Big Pine and No Name keys); (2) use road surveys and radiotelemetry to determine population density, sex ratio, and age structure of the core area Key Deer population; and (3) synthesize the expansive historical data with current data-collection efforts to determine potential Screwworm impacts on mortality and sex ratios.

Field Site Description

Key Deer occupy 20–25 islands in the Lower Keys within the boundaries of the National Key Deer Refuge (NKDR; Fig. 1). Two adjacent islands, Big Pine Key

(2522 ha) and No Name Key (459 ha), form the core habitat for Key Deer (Lopez et al. 2005). Big Pine and No Name keys are urbanized islands characterized by extensive roads and structure development. Big Pine Key has higher road density (0.05 km/ha) and development than the other major population-supporting islands (outside the core area) in the Key Deer range (Cudjoe = 0.04 km/ha, Sugarloaf = 0.03 km/ha; Parker 2006).

The Florida Keys form a low-lying archipelago, with the majority of the land rising only 1–2 m above mean sea level (Hoffmeister 1974). The Lower Keys likely began as an oolitic mound that slowly grew in size as ooids (calcareous sand spheres) were added and covered the existing corals. This limestone is often covered by soil ranging from blue-grey marl to black peat (Dickson 1955).

Vegetation of West Indian origin dominates the Lower Keys and varies between islands (Dickson 1955). Vegetation types change according to elevation with *Rhizophora mangle* L. (Red Mangrove), *Avicennia germinans* L. (Black Mangrove), and *Laguncularia racemosa* Gaertn. (White Mangrove) forests occurring near sea level. This gives way to transitional *Conocarpus erectus* L. (Buttonwood) areas as elevation increases. At the highest elevations, the buttonwood areas transition into hammock (e.g., *Piscidia piscipula* Sarg. [Jamaica Dogwood] and *Metopium toxiferum* Krug and Urb. [Poisonwood]) and pineland (e.g., *Pinus elliottii* Engelm. [Slash Pine] and *Croton linearis* Jacq. [Pineland Croton]) upland forests intolerant of salt-water. Freshwater marshes (e.g., *Cladium jamaicense* Crantz [Saw Grass] and *Acrostichum aureum* L. [Golden Leather Fern]) inhabit lowland areas surrounded by upland forests or lie between upland areas and transition zones. All study islands support wide-ranging pine rocklands (preferred deer habitat; Lopez et al. 2005) and have the most extensive year-round freshwater in the Keys (USFWS 1999).

Methods

Key Deer have been intensively monitored since the 1960s; providing an unusual depth and breadth of data including mortality and health analyses, population structure, habitat use, and behavior (e.g., Braden et al. 2008; Hardin et al. 1976; Lopez et al. 2003, 2016; Nettles et al. 2002; Roberts et al. 2006; Parker et al. 2008a, b, 2017a; Silvy 1975; Villanova 2015). We synthesized historical and newly collected data to determine population structure and potential Screwworm impacts.

Key Deer mortality

USFWS personnel and collaborators have collected detailed mortality data for Key Deer since 1968 (Lopez et al. 2003, Silvy et al. 1975). All mortalities were recorded with cause, location, date, and appropriate demographic data. The USFWS and collaborating biologists recorded Key Deer mortalities throughout their range via direct sightings, citizen and law enforcement reports, and observations of *Cathartes aura* L. (Turkey Vulture) (Lopez et al. 2003). Age, sex, and body mass were recorded for each dead animal, and all road-related deer-mortality locations were entered into a geographical information system (GIS) and accompanying database. A strong partnership with local residents and law enforcement, high species visibility, and ubiquity of roads and private/public buildings allowed recording of a high proportion of mortalities. The dedication of USFWS to maintain this mortality monitoring has resulted in a robust mortality time-series dataset. During the Screwworm incident, these deer mortalities continued to be recorded, and in many cases, cause of death was listed as euthanasia, though presence of Screwworm infection was noted. We calculated spatial distribution of Screwworm-related mortalities using a density estimator in ArcMap 10.1 (Environmental Systems Research Institute, Redlands, CA).

Road surveys and radiotelemetry

Mark–resight and distance-based population densities, sex ratios, habitat selection, and spatial use were estimated for 1968–1972 (Hardin et al. 1976, Silvy 1975), 1998–2001 (Lopez et al. 2004), 2002–2004 (Roberts et al. 2006) and 2016–2017 (current study). Deer were captured throughout these studies using portable drive nets, drop nets, and hand capture (Lopez et al. 1998, Silvy 1975, Silvy et al. 1975), and marked in a variety of ways depending on sex and age. Density, sex ratios, and habitat use were estimated using mark–resight and radiotelemetry methods (Lopez 2001, Lopez et al. 2016, Roberts 2005, Silvy 1975).

In radiotelemetry efforts, a battery-powered radio transmitter was attached to collar material. In the historical studies (1968–1972, 1998–2001, 2002–2004), each captured animal received an ear tattoo, which served as a permanent marker (Silvy 1975). We did not use tattoos in the current data collection and only collared females. During the current study, we conducted Key Deer radiotelemetry during the work week (Monday–Friday) to minimize scheduling impacts on USFWS personnel.We devoted 2 weekdays to tracking deer on North Big Pine Key (north of Watson Boulevard.) and another 2 days on South Big Pine Key and No Name Key, and 1 day a week to locating all deer throughout all of these islands. Tracking times were varied such that if one geographic location was surveyed in the morning, the next time that location would be surveyed in the evening, which served to minimize the impacts of deer temporal behavior patterns. We calculated 95% ranges and 50% core areas of individual radiocollared Key Deer using a fixed-kernel home-range estimator in DNRGPS (Version 6.1.0.6; Minnesota Department of Natural Resources, St. Paul, MN) and ArcMap 10.1 (ESRI, Redlands, CA). Current study capture and radiocollaring efforts were approved by Texas A&M University (AUP# 2016-0366).

Road surveys were conducted from January 1969 to March 2001 on Big Pine and No Name keys along standardized routes (Lopez 2001, Lopez et al. 2004, Silvy 1975). These surveys were designed to provide an index (i.e., average number of deer seen/km) to the population size and structure of Key Deer (i.e., number, sex, and age). In 2002–2004, we calibrated distance sampling (Buckland et al. 1993, Pierce 2000) against concurrent mark–resight and radiotelemetry efforts, allowing a rapid density estimation technique that reduced the need to capture and mark deer for density estimation in the core habitat (Roberts et al. 2006, Schmidt et al. 2007).

To update Key Deer density estimates following the peak of the Screwworm infestation in October 2016, we conducted conventional distance sampling along standardized routes on Big Pine and No Name keys (Fig. 2; Pierce 2000, Roberts et al. 2006, Schmidt et al. 2007). We attempted to expand these methods to Cudjoe and Sugarloaf keys; however, these efforts proved inefficient due to low numbers of deer observed. Thus, results presented here focus primarily on the core populations located on Big Pine and No Name keys.

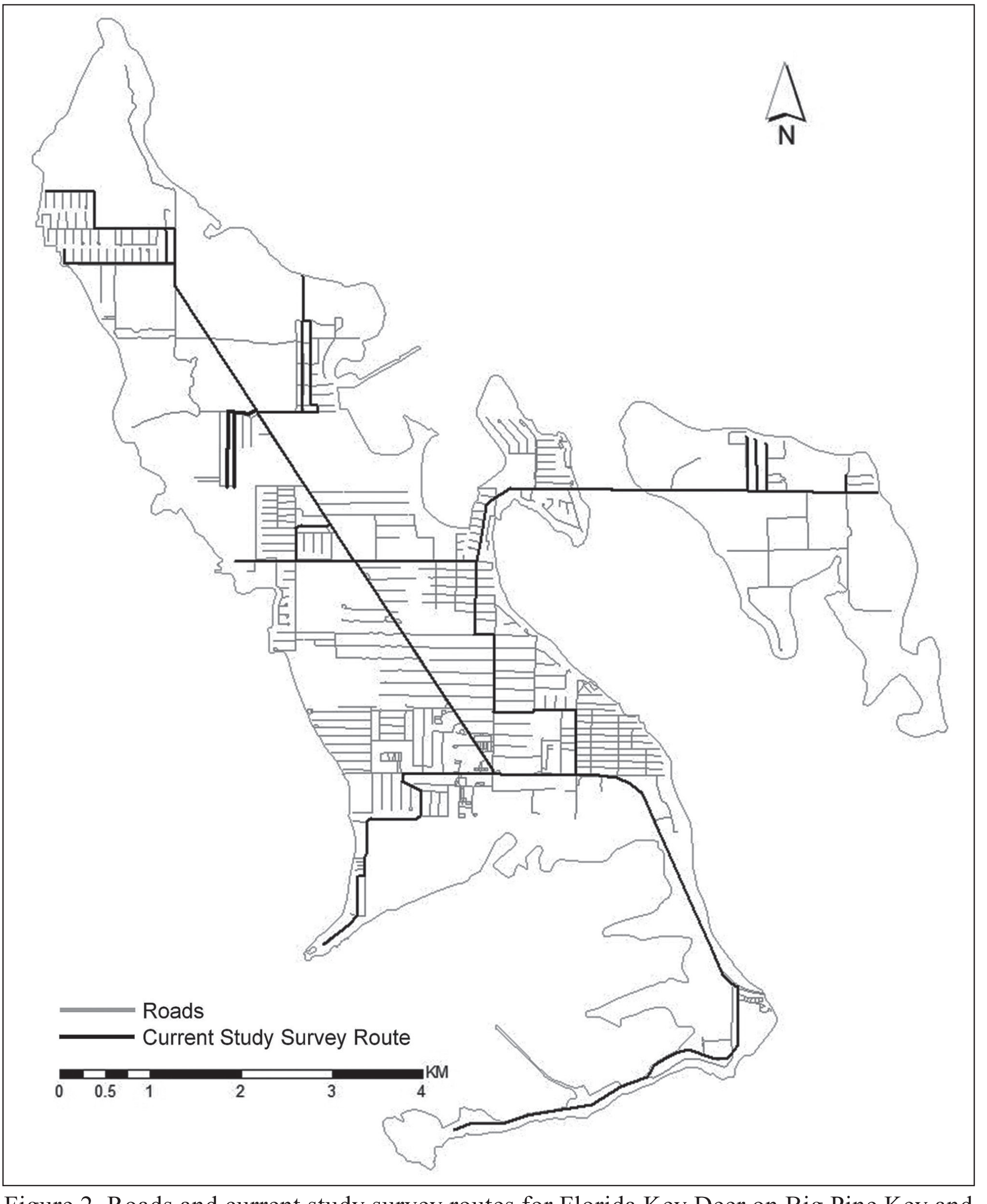

Figure 2. Roads and current study survey routes for Florida Key Deer on Big Pine Key and No Name Key, FL, 2016.

We conducted road surveys along each route at sunrise and sunset (November–December 2016) using a driver and 2 observers (average travel speed of 25–40 km/hr) who recorded the number of deer observed, distance, location, sex, and age (fawn, yearling, adult). Perpendicular distance estimates were obtained using a laser rangefinder from the centerline of the survey route. We used Program DISTANCE (Version 7.3; www.distancesampling.org) to estimate density and population size stratified by month (i.e., both islands combined). We right truncated perpendicular distance data at 100 m, with model-fit parameters for detection probability, density, cluster size, and encounter rates stratified by month. We used uniform and half-normal models based upon model fit (Kolmogorov–Smirnov Test), with model selection based upon Akaike information criterion (AIC). We estimated expected cluster size by regression of log(s[i]) on g(x[i]) for all sightings.All statistical analyses were performed using R (Version 3.53; www.r-project.org).

To validate our current density estimates we compared them with estimates determined for 1971–2016. We estimated the annual rate of growth for density estimates for 1971–2016, and compared that rate of growth to the annual rate obtained from mortality and annual USFWS road survey data.

Results

Key Deer mortality

Approximately 14% (9–20%, see estimates below) of the Key Deer population was euthanized and/or died due to Screwworm infections (n = 135 deer mortalities). The majority of these mortalities occurred during October 2016 (Fig. 3). Screwworm-related mortalities were concentrated in several urban areas that traditionally have high Key Deer densities or represent a movement corridor (Fig. 4). Most of these mortalities were adult males (n = 111 total adult male mortalities, n = 1 yearling male mortality, n = 2 male fawn mortalities, n = 10 unknown male mortalities).

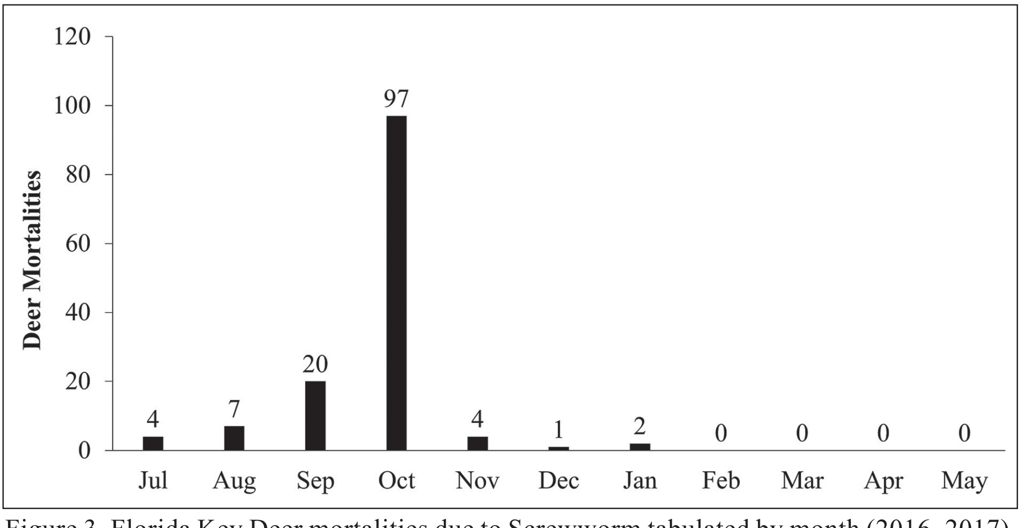

Figure 3. Florida Key Deer mortalities due to Screwworm tabulated by month (2016–2017), Lower Florida Keys, FL.

Female mortality was evenly distributed (n = 10 total female mortalities; all age categories contained 1–3 individuals). One additional deer mortality of unknown sex and age was attributed to Screwworm. The vast majority of these infected deer were found on Big Pine Key (n = 124, Fig. 4); however, mortalities also were found

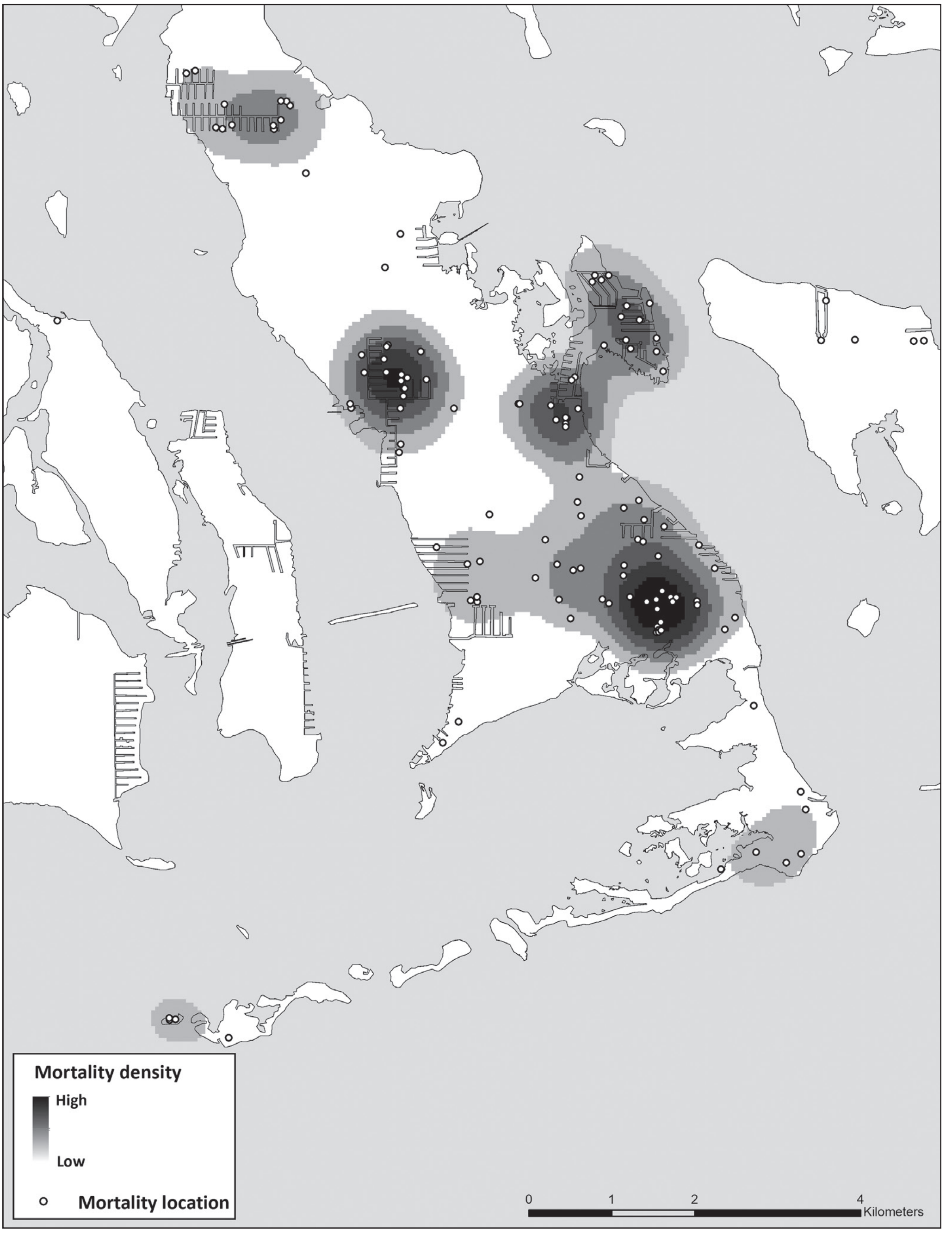

Figure 4. Florida Key Deer mortalities due to Screwworm in 2016 on Big Pine Key, FL, with a mortality density overlay indicating areas of higher mortality.

on No Name (n = 5), Middle Torch (n = 1), the Munsons (n = 4) and Sugarloaf (n = 1) keys. Mortalities increased from the initial Screwworm detection in July 2016 (n = 4) to the end of October 2016 (n = 97); however, Screwworm-related mortalities began to decline in the middle of October 2016 and dropped much lower by November 2016, with only 7 Screwworm-related mortalities recorded from 1 November 2016–31 January 2017 (Fig. 3) and 0 mortalities after January 2017.

Key Deer population abundance and structure

Key Deer abundance. Immediately following the peak of the Screwworm outbreak, we conducted road surveys on Big Pine and No Name keys (number of Key Deer observations [n] = 567, number of transects [k] = 30, overall length [L] = 542 km in November; n = 367, k = 20, L = 361 km in December), yielding a pooled post-Screwworm incident population estimate of 860 Key Deer (Half normal model with 1 cosine adjustment term [2nd order], %CV = 3.33, 95% CI = 563–1313) on those 2 islands (N = 883, %CV = 8.43, 95% CI = 745–1047 in November; N = 825, %CV = 8.17, 95% CI = 699–974 in December). Adding 135 Key Deer to our estimate suggests the Key Deer population on Big Pine and No Name keys was potentially 995 deer (95% CI = 698–1448 deer) immediately prior to the infestation.

We derived the population growth rate (3.5%) using historical population estimates (Lopez 2001, Roberts 2005, Silvy et al. 1975) in an effort to further validate the pre-Screwworm population estimate. We used the historical population estimates and the growth rate to provide a very rough population estimate for the Key Deer population immediately prior to the Screwworm incident (n = 806–857; Lopez et al. 2016). This rough population estimate was within the CI (95% CI = 698–1448 deer) that we calculated using distance surveys above.

Ranges and fawning. Historical data indicated substantial overlap between areas of high numbers of Screwworm mortalities (e.g., southern portion of Big Pine Key) and areas where males concentrated (from historical studies). This pattern was particularly evident during the breeding season (September–January; USFWS 1999) and included transition areas where males moved through in search of females. By 30 May 2017 of the current study, USFWS personnel had 74 full tracking days and 1 partial day (radiotelemetry training on January 20). USFWS personnel successfully tracked all remaining radio-collared deer (20 January 2017–30 May 2017) and recorded 1467 radiotelemetry locations (visual: n = 782 observations; homing: n = 685 observations). We used the radiotelemetry locations for 20 January–30 May to calculate 95% ranges and 50% core areas for Key Deer. A single Key Deer was removed from analyses due to insufficient observations. The remaining 29 Key Deer had relatively large 95% ranges (mean = 69 ha, SD = 77 ha, min–max = 19–333 ha) and 50% core areas (mean = 12 ha, SD = 12 ha, min–max = 4–50 ha). These range values fall within historical range-size estimates for females (mean = 42–101 ha; Lopez 2001). The number of observations for each Key Deer (mean = 50 observations/deer) is relatively low for kernel estimation and likely contributed to the high variances. The observed Key Deer had high site fidelity and remained clustered around capture sites.

The Key Deer fawning season generally begins in April and can extend into July and August. Marked females began to show evidence of pregnancy (e.g., heavily gravid, lactation evident) in late March and early April 2017. By 2 May, several marked females had new fawns (n = 5 females), while others were lactating (n = 7 females) or heavily gravid (n = 3 females). By 30 May, 3 additional marked females had fawns (n = 8 total females), and others were lactating (n = 4 females) or heavily gravid (n = 1 female). The remaining marked Key Deer (n = 12 females, not yet observed as pregnant or fawned) did not display obvious indicators of pregnancy or recent parturition. However, the status of an additional 4 marked females could not be confirmed. All observed fawns looked healthy with no signs of temporary or persistent injuries or Screwworm infestation.

Key Deer sex ratio and age structure. The ratio of all females to adult males rose during the 12-month pre-Screwworm period to the 6 months post-Screwworm period. Key Deer sex and age structure shifted with adult male mortalities; current sex ratios (females:adult males) are slightly higher (4.12) compared to the historic average (3.76:1). This indicated an outsized impact of New World Screwworm on adult males. However, the ratio of all females to all males (regardless of age) declined from 2.55:1 to 1.89:1 (Table 1).

Discussion

Mortality

Screwworm disproportionately impacted adult males in the Key Deer population. The fall season is the breeding period for Key Deer when males often spar and receive minor injuries (Nettles et al. 2002, Quist et al. 2002), increasing the risk of Screwworm infection. As a result, the majority of infested Key Deer were adult males (n = 111, 82% of total infested). In contrast, the age-distribution of infested females was much more evenly distributed, as females are often injured due to general environmental factors rather than intraspecies conflict. This sex-biased impact is reflected in the increase in the ratio of adult females to adult males. The reduction of adult males perhaps allowed more subadult male movement (including chasing females) leading to lower ratio of all females to all males post-Screwworm in subsequent surveys. The ratio of observed females to observed males also likely declined during the peak rut as males moved farther and more frequently and became more visible. A temporary reduction in the number of adult males is not expected to impact the population as younger males experienced lower Screwworm-based mortality and would be available to mature into adult males in subsequent years. The mortality of females and fawns would be expected to increase if Screwworm flies were still broadly present during the spring fawning period.

Table 1. Sex ratios observed prior to, during and after the Screwworm infestation (F = females, AM = adult males, M = males), Lower Florida Keys, FL, 2016–2017.

	12 month pre-Screwworm	Peak rut Screwworm Period	6 months post-Screwworm
F:AM	3.76	1.80	4.12
F:M	2.55	1.23	1.89

Density and population growth

Direct mortality of 135 Key Deer resulted in an immediate decline in overall abundance and core habitat population density. Road-based distance-sampling estimates suggested the Key Deer population on Big Pine and No Name keys was less than 1000 after the Screwworm infestation. Road-based sampling can increase concerns of sampling bias. However, sampling from roadways in this type of setting is unavoidable, as roads cover a substantial proportion of the landscape in urbanized areas (Fig. 2). Within urbanized landscapes, sample designs that attempt to avoid roads can themselves become biased due to unrepresentative sample selection across the broader urban matrix, resulting in an underestimation of true spatial variability.

The number of Screwworm-related mortalities markedly declined from the peak infestation period. The decline in Screwworm-related mortalities post-November 2016 (n = 7 after 1 November) suggests that dewormer treatments, application of sterile flies, and decline in rutting behavior likely resulted in a decline in the Screwworm infestation on the Key Deer population.

With the eradication of Screwworms from the Florida Keys by spring of 2017, managers avoided a negative impact on females and fawns during the 2017 fawning season. Additionally, younger males were largely unaffected by the Screwworm outbreak and matured into adult males in 2017. Historical growth data suggested that a healthy Key Deer herd supported by maturing juvenile males and females would recover. Unfortunately, Hurricane Irma made landfall in September 2017 and further impacted Key Deer habitat and population (Parker et al. 2017b). This confounded further long-term assessment of Key Deer population recovery from Screwworm infestation.

Overall

The rapid response efforts by USDA, USFWS, and other key agencies reduced Screwworm-related mortalities in Key Deer. Application of sterile flies and dewormer preventative treatments appears to have been a critical management strategy in helping eliminate Screwworm infections prior to the 2017 fawning season. In the event that Screwworm infestation reoccurs on certain islands or within core Key Deer habitat, a general management strategy consisting of such proven response actions based on probable population density thresholds should be considered. This will require consistent population monitoring over the next several years.

Acknowledgments

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