EXPLORATION OF OPPORTUNITIES TO REDUCE KEY DEER ROAD MORTALITY ALONG US HIGHWAY 1 AND OTHER ROADS, NATIONAL KEY DEER REFUGE, FLORIDA, USA

by

Marcel P. Huijser, PhD

&

James S. Begley, MSc

FINAL REPORT

Western Transportation Institute
College of Engineering, Montana State University,
P.O. Box 174250. Bozeman, MT 59717-4250

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16. Abstract

We investigated Key deer mortality data and found that about 75% of all reported Key deer mortalities were related to collisions with vehicles. We investigated where the greatest concentrations of Key deer-vehicle collisions were after the eastern section of US Hwy 1 was mitigated with a wildlife fence, 2 underpasses, and 4 deer guards. We also investigated the effectiveness of these mitigation measures in reducing Key deer-vehicle collisions. The wildlife fence and associated mitigation measures along the eastern section of US Hwy 1 on Big Pine Key were highly effective (81.3-93.9%) in reducing Key deer-vehicle collisions along that road section. However, there was an increase in collisions in the unmitigated section of US Hwy 1, both in absolute numbers and expressed as a percentage of the total Key deer population size. Thus, the overall Key deer road mortality on US Hwy 1 was not reduced but it was moved from the mitigated section to the unmitigated section of US Hwy 1. After mitigation, a significant hotspot of Key deer-vehicle collisions appeared at the western fence end. Additional significant Key deer-vehicle collision hotspots occurred furter west along the unmitigated highway section on Big Pine Key. In order to reduce the overal number of Key deer-vehicle collisions along US Hwy 1, the entire section of US Hwy 1 on Big Pine Key would need to be mitigated. Ideally, the wildlife fence should be extend to the western side of Big Pine Key with additional safe crossing opportunities for Key deer and other wildlife species. However, the secion of US Hwy 1 that is currently still unfenced has many buildings and access roads for business and residences. Rather than recommending a particular mitigation option for this road section, we summarized the pros and cons of eight different strategies aimed at reducing Key deer-vehicle collisions along the developed section of US Hwy 1, including a "No Action" option.

17. Key Words Collisions, connectivity, corridors, crashes, crossing structures, data analysis, fences, Florida, habitat, highway, hotspot, key deer, mitigation measures, National Key Deer Refuge, *Odocoileus virginianus clavium*, plan, procedures, prioritization, ranking, safety, strategy, strategies, tools, tunnels, underpasses, wildlife, wildlife–vehicle collisions	**18. Distribution Statement** Unrestricted. This document is available through U.S. Fish & Wildlife Service, and WTI-MSU.

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SUMMARY

In 1957, the National Key Deer Refuge (NKDR), one of four national wildlife refuges in the Florida Keys National Wildlife Refuges Complex (FKNWRC), was established in the Lower Florida Keys. The FKNWRC was established to protect the endangered Key deer (*Odocoileus virginianus clavium*) along with other endangered species and the habitat they depend on. At the time, hunting had reduced the Key deer population to less than 50 individuals. Since then the Key deer population has increased to an estimated 1,000 individuals. However, about 10-15% of the Key deer are killed on the roads every year, especially on US Hwy 1 on Big Pine Key (Average Annual Daily Traffic about 18,000).

In 2001 and 2002, 1.6 mi (2.6 km) of US Hwy 1 was mitigated with a 2.4 m (8 ft) high fence, 2 underpasses, and 4 deer guards. Other researchers found that the mitigation measures reduced Key deer collisions by about 90% along this road section, Key deer use the underpasses, and Key deer use has been increasing with the age of the structures. However, Key deer collisions continued to increase overall, i.e. on other non-mitigated road sections, especially on the western section of US Hwy 1. While the remaining unfenced road section of US Hwy 1 may be more difficult to mitigate because of houses, businesses, sideroads and driveways, USFWS would like to explore additional opportunities with partners and the community to reduce Key deer road mortality.

We investigated the Key deer mortality data and found that about three in every four reported Key deer mortalities (75.5% (SD=10.2)) resulted from a collision with a vehicle. We investigated where the greatest concentrations of Key deer-vehicle collisions were after mitigating the eastern section of US Hwy 1 through a Kernel density hotspot analysis. Of all the roads on Big Pine Key and surrounding islands, only the unmitigated western section of US Hwy 1 on Big Pine Key had road sections with Key deer roadkill concentrations in the highest Kernel density categories. There were two main hotspots; one on the west side of Big Pine Key (opposite of the canals (W. Cahill Ct.) until Deer run Tr.), and one at the west or north end of the wildlife fence (opposite of the St. Peter Catholic Church), extending further west till Cunningham Ln. If roadkill of Key deer is to be reduced further, the efforts should be concentrated on the unmitigated section of US Hwy 1, especially at the hotspots described above.

Based on a Before-After Control-Impact (BACI) analysis, the wildlife fence and associated mitigation measures along the eastern section of US Hwy 1 on Big Pine Key were highly effective (93.9%) in reducing Key deer-vehicle collisions along that road section. However, the reduction in Key deer road mortality in the fenced section was accompanied by an increase in collisions in the unmitigated section of US Hwy 1, and the total number of roadkilled Key deer continued to increase. When corrected for the population size, Key deer road mortality was similar before and after highway mitigation for all roads combined as well as for US Hwy 1 (mitigated and unmitigated section combined). Similar to the absolute numbers, the percentage of roadkilled Key deer in relation to the population size sharply decreased in the mitigated section of US Hwy 1, but substantially increased in the unmitigated section of US Hwy 1. Thus the overall Key deer road mortality along US Hwy 1 was not reduced but it was moved from the mitigated section to the unmitigated section of US Hwy 1. After mitigation, a significant hotspot of Key deer-vehicle collisions appeared at the west/north fence end of the mitigated section of

US Hwy 1, likely as a result of some Key deer following the fence and crossing at-grade in higher than average numbers at the fence end. Other significant Key deer-vehicle collision hotspots after mitigation occurred further west along the unmitigated highway section on Big Pine Key.

The BACI approach estimated that the mitigation measures were highly effective (93.9%) in reducing Key deer-vehicle collisions in the fenced section of US Hwy 1. However, the BACI approach assumes that the number of collisions in the control section is not influenced by the fenced section. But given the significant fence end effect extending into the control section, we know that the control section is at least partially influenced by the fenced section. If the effectiveness of the fenced road section is calculated based on a simple Before-After approach (excluding a correction for the control section), the measures reduced Key deer roadkill by 81.3% in the mitigated road section. Note that the downside of a Before-After approach is that it does not correct for the increase in Key deer population size and this leads to an underestimation of the effectiveness of the mitigation measures in reducing Key deer-vehicle collisions. Nonetheless, the mitigation measures were at least 81.3% effective in reducing Key deer-vehicle collisions in the fenced road section.

The wildlife fence and associated measures were highly effective (81.3-93.9%) in reducing Key deer-vehicle collisions along the fenced section of US Hwy 1. However, in order to reduce the overal number of Key deer-vehicle collisions along US Hwy 1, the entire section of US Hwy 1 on Big Pine Key needs to be mitigated. Ideally, the wildlife fence should be extend to the western side of Big Pine Key with additional safe crossing opportunities for Key deer and other wildlife species. However, the section of US Hwy 1 that is currently still unfenced has many buildings and access roads to business and residences. This means that there are many competing interests. Implementing mitigation measures that are effective in reducing Key deer-vehicle collisions and that also provide safe crossing opportunities for Key deer and other wildlife species, will affect other interests on and along US Hwy 1.

We summarized the pros and cons of eight different strategies aimed at reducing Key deer-vehicle collisions. We included a strategy “No Action” as we recognize that there are many and sometimes conflicting interests that make it challenging to reduce Key deer-vehicle collisions along the western portion of US Hwy 1 and that taking “no action” may be the preferred strategy. The eight strategies described in this report are:

- Strategy 0: No Action
- Strategy 1: Mitigate Collisions at the Fence End Only
- Strategy 2: Fence the Remaining Section of US Hwy 1 Between the Highway and the Adjacent Buildings (Businesses, Residences)
- Strategy 3: Fence the Remaining Section of US Hwy 1 Behind the First Row (or Block or Several Blocks) of Buildings (Businesses, Residences)
- Strategy 4: Combine Wildlife Fences (Strategy 3) with Safe Crossing Opportunities for Key Deer: Animal Detection Systems
- Strategy 5: Combining Wildlife Fences (Strategy 3) with Safe Crossing Opportunities for Key Deer: Wildlife Underpasses or Overpasses
- Strategy 6: Bypass for Big Pine Key
- Strategy 7: Rebuild the Railroad, No Access for Vehicles from Mainland

Note that these mitigation options are not endorsed by any organization, have no planning status, are not necessarily realistic, and are only meant as a free exploration of the pros and cons of a wide variety of strategies.

1. INTRODUCTION

1.1. Background

In 1957, the National Key Deer Refuge (NKDR), one of four national wildlife refuges in the Florida Keys National Wildlife Refuges Complex (FKNWRC), was established in the Lower Florida Keys. The FKNWRC was established to protect the endangered Key deer (*Odocoileus virginianus clavium*) along with other endangered species and the habitat they depend on. At the time, hunting had reduced the Key deer population to less than 50 individuals. Since then the Key deer population has increased to an estimated 1,000 individuals. Most of the deer are found from Sugarloaf Key (west) to Big Pine Key and No Name Key (east), partially aided by reintroduction on some islands (Parker et al., 2008). An estimated 80% of the Key deer occur on Big Pine Key and No Name Key (Personal communication Daniel Clark, USFWS/FKNWRC). Some parts of the islands have been urbanized, resulting in a mosaic of natural habitat, residential, and commercial lots. This development has especially occurred on Big Pine Key. Additionally, tourism increased substantially since the 1980s (peak season November-April). This has resulted in an estimated two million visitors per year, most of whom travel on US Hwy 1 towards Key West. The Average Annual Daily Traffic (AADT) for US Hwy 1 on Big Pine Key has grown from about 16,000 in 2011 to about 18,000 in 2016 (KBP Consulting, Inc., 2017). Since there are no natural predators for key deer, conflicts with humans, including vehicle collisions, are the most important causes of mortality for the deer.

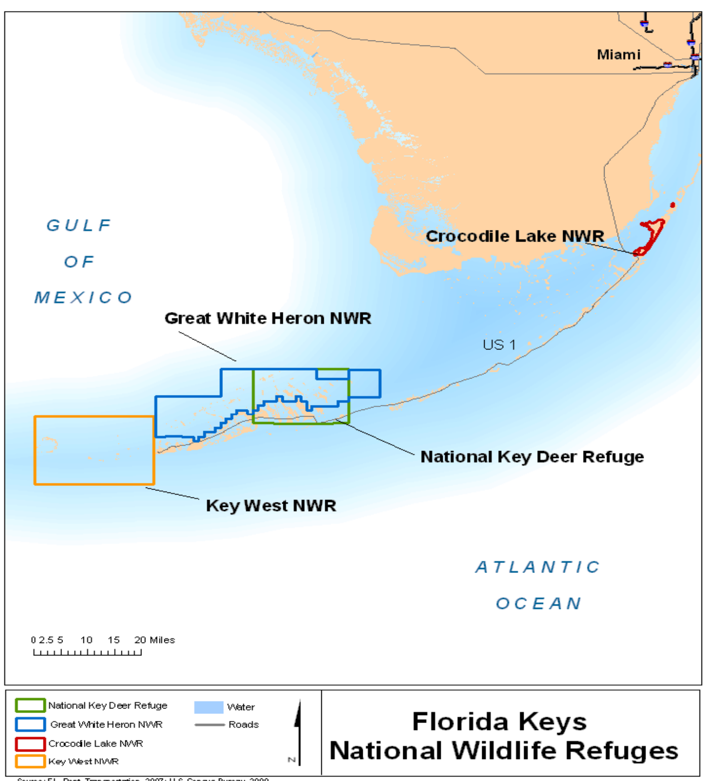

Figure 1: The location of the National Key Deer Refuge as part of the Florida Keys National Wildlife Refuges Complex, Florida, USA.

It is estimated that about 10-15% of all annual Key deer mortalities are due to vehicle collisions (Personal communication Kate Watts, USFWS/FKNWRC), with over half of all roadkill occurring along US Hwy 1. US Hwy 1 is the only highway linking the Florida Keys to the mainland of peninsular Florida. Most of the Key deer-vehicle collisions occur at dawn and dusk. FKNWRC staff have recorded Key deer mortality along the roadsides since 1966. The data allow managers to identify collision hotspots along the roadway. USFWS has successfully worked with interagency partners including the Florida Department of Transportation (FDOT) and Monroe County to address Key deer highway mortality along the eastern portion of US Hwy 1 on Big Pine Key, an area with minimal human development (Figure 2). This was accomplished through installation of two wildlife underpasses and wildlife fences along the roadside to keep deer from accessing the highway. Furthermore, a wildlife guard (similar to a cattle guard) was installed at the western fence end. Three additional wildlife guards and a gate were installed at four access roads. These measures were designed to keep Key deer from entering the fenced road corridor. Furthermore, US Hwy 1 and county roads on Big Pine Key have reduced speed limits (reduced from 65 MPH to 45 MPH on US Hwy 1 (35 MPH at night), 45 MPH to 30 MPH on Key Deer Blvd, and to 25 MPH on other roads). USFWS is interested in continuing work to identify opportunities with partners and the community to further minimize road mortality along US Hwy 1, while being sensitive to the needs of other stakeholders, including vehicle access to residences and businesses. In addition, USFWS is interested in an evaluation of the existing mitigation measures along US Hwy 1, and exploring opportunities with partners and the community for reducing collisions along the following county roads on Big Pine Key and No Name Key: Key Deer Blvd, Wilder Rd-South St.- Ave. B-State Rte 4a (incl. on No Name Key), and Watson Blvd. (Figure 2).

Figure 2: The highways and roads included in this project: Mitigated section of US Hwy 1 (green), Unmitigated section of US Hwy 1 (red), Key Deer Blvd (orange), Wilder Rd-South St.- Ave. B-State Rte 4a (yellow), Watson Blvd (blue) on Big Pine Key and No Name Key.

1.2. Existing Highway Mitigation for Key Deer

In 2001 and 2002, a 1.6 mi (2.6 km) section of US Hwy 1 was mitigated with a 2.4 m (8 ft) high fence, 2 underpasses, and 4 deer guards (Braden et al., 2008; Parker et al., 2011) (Figures 3-7). Based on a Before-After comparison, the mitigation measures reduced Key deer collisions by about 90% (Parker et al., 2011). However, Key deer collisions continued to increase overall, i.e. on other non-mitigated road sections (Parker et al., 2011). The increase in Key deer-vehicle collisions was attributed to a continuing increase in Key deer population size and growing traffic volume, especially on US Hwy 1 (Parker et al., 2011). Key deer use the underpasses, and Key deer use has been increasing with the age of the structures (Braden et al., 2008; Parker et al., 2011). While the remaining unfenced road section of US Hwy 1 may be more difficult to mitigate because of houses, businesses, sideroads and driveways, USFWS would like to explore additional opportunities with partners and the community to reduce Key deer road mortality. Note: Hurricane Irma blew over large sections of the wildlife fence along US Hwy 1 in September 2017. It is scheduled to be repaired in 2019.

Figure 3: The mitigated highway section of US Hwy 1 on Big Pine Key.

Figure 4: The wildlife fence to Keep Key deer off US Hwy 1, Big Pine Key, Florida.

Figure 5: The northern wildlife underpass aimed at providing safe crossing to Key deer and other wildlife, US Hwy 1, Big Pine Key, Florida.

Figure 6: The wildlife guard at the fence end, US Hwy 1, Big Pine Key, Florida.

Figure 7: A wildlife guard at one of the side roads of US Hwy 1, Big Pine Key, Florida.

Other mitigation measures aimed at reducing collisions with Key deer along both the mitigated and unmitigated section of US Hwy 1 on Big Pine Key include low maximum posted speed limits (45 MPH during the day, 35 MPH during the night), mobile speed radar units informing drivers of the speed of their vehicle, parked police cars (no law enforcement personnel present), and a variety of warning and informational signs (Figure 8-11).

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Figure 8: Low posted maximum speed limit (45 MPH during day, 35 MPH during night), US Hwy 1, Big Pine Key, Florida.

Figure 9: Mobile speed radar, US Hwy 1, Big Pine Key, Florida.

Figure 10: Parked police car, no law enforcement personnel present, US Hwy 1, Big Pine Key, Florida.

Figure 11: Key deer warning sign, US Hwy 1, Big Pine Key, Florida.

Mitigation measures on secondary roads on Big Pine Key include low maximum posted speed limits (25 or 30 MPH), speed bumps, and a variety of warning and informational signs (Figures 12-14). In addition, feeding of Key deer is illegal as unnatural food may be a threat to the health of the Key deer, can help spread diseases, disrupts their natural interaction with the environment (affects ecological integrity), and encourages them to spend more time on and along roads where they are exposed to vehicles. Despite substantial enforcement, feeding of Key deer is common.

Figure 12: Low posted speed limit (25 MPH) aimed at reducing Key deer-vehicle collisions on one of the secondary roads, Big Pine Key, Florida.

Figure 13: Speed bump (with cross walk pattern) aimed at reducing Key deer-vehicle collisions on one of the secondary roads, Big Pine Key, Florida.

Figure 14: Key deer warning sign and notice that feeding Key deer is unlawful, along one of the secondary roads, Big Pine Key, Florida.

1.3. Recent Mortality Through an Outbreak of New World Screwworms

In 2016 and 2017, Key deer suffered mortality because of an outbreak of New World screwworms (*Cochliomyia hominivorax*). New World screwworms are fly larvae (maggots) that can infest mammals, including Key deer. The flies are attracted to open wounds and lay their eggs in these wounds. The larvae then eat live tissue and can eventually cause the death of the animal. Male Key deer appear especially vulnerable during the rut as fighting can result in open wounds. To combat the outbreak, sterile male New World screwworms were released twice per week until about 3 months beyond the last fertile fly is detected or beyond the last infestation case, with an additional 3 months of surveillance. In addition, an anti-parasitic preventative treatment drug was administered to the Key deer in two ways: 1. Manual feeding of the deer on a weekly basis by applying the drug on the food and marking the treated animals with paint, and 2. Supplying a grain mix to the deer in more remote areas in troughs that have paint rollers that allow for the topical application of the drug. Note that feeding the Key deer is normally illegal. The feeding described above was an emergency procedure to apply the anti-parasitic drug and to reduce Key deer mortality as a result of the New World screwworm outbreak. Note that the orally administered anti-parasitic drug is only effective for one week. Therefore, the drug needed to be applied regularly. Female key deer may also be susceptible to infestation during the birthing process, so additional monitoring was conducted during the spring of 2017 to document mortalities associated with this life stage. By January 2018, New World screwworms were believed to no longer be present on the Florida Keys (Personal communication Kristie Killam, USFWS/FKNWRC) and Key deer populations had returned to being stable and within range of population estimates before the New World screwworm outbreak.

1.4. Tasks

Task 1: Obtain data:

a. Key deer – vehicle collision data (provided by FKNWRC) between 9 March 1966 and 31 Dec 2016 for US Hwy 1 and other roads in the range of the Key deer. Note that FKNWRC manages crash and carcass data for Key deer, including from collisions that occurred along US Hwy 1 and the county roads of interest to this project. This data is collected opportunistically by FKNWRC and Florida Fish and Wildlife Conservation Commission law enforcement. Not every dead Key deer and cause of death is reported and recorded.
b. Key deer population data (provided by FKNWRC) as it has been periodically estimated in the period between 1966 and 2016.
c. A map (provided by FKNWRC staff) for Big Pine Key and No Name Key that shows the land ownership (e.g. refuge boundaries and parcels, other areas that have protected habitat (e.g. through partnership agreements with other land management agencies).

Task 2: Identify hotspots and assess the effectiveness of the existing mitigation measures:

a. Identify and prioritize road sections for potential future mitigation measures aimed at further reducing Key deer-vehicle collisions and maintaining habitat connectivity for Key deer based on the spatial distribution of Key deer-vehicle collisions along the road sections of interest (Figure 2).
b. Assess the long-term effectiveness of the mitigation measures along the eastern portion of US Hwy 1 in reducing Key-deer-vehicle collisions.

Task 3: Conduct a site visit and conduct the following activities:

a. Interview FKNWRC law enforcement staff and park rangers about road sections where they see live Key deer most often on or alongside the road and factors that may influence Key deer road mortality. It is important that potential mitigation measures do not result in a barrier in areas where Key deer may currently successfully cross the road.

b. Conduct interviews with representatives of FKNWRC and home owners and businesses (e.g. through home owners or business associations) and ask them about their perception regarding:
    a. The magnitude of the Key deer-vehicle collisions and a potential desire to reduce these collisions.
    b. The need for Key deer to continue to be able to access areas on both sides of the road (habitat connectivity through safe crossing opportunities).
    c. A range of different measures aimed at reducing Key deer-vehicle collisions and proving safe crossing opportunities for Key deer. The measures may include wildlife fences (along roads and/or along property boundaries set back from the roads), underpasses, overpasses, animal detection systems, speed management, warning signs (standard or enhanced). Note: Standard or enhanced wildlife warning signs are likely not effective in reducing wildlife-vehicle collisions (Huijser et al., 2015a). Note: Short sections of wildlife fences (<3 mi in road length) are, on average, substantially less effective and very variable in their effectiveness compared to longer fenced road sections (Huijser et al., 2016). Note: Drivers typically drive a speed that reflects the design speed rather than the maximum posted speed limit. Therefore, substantially lowering the maximum posted speed limit below the design speed is not an effective strategy (Huijser & Ferraz, 2015).
    d. A more intensive outreach effort to visitors to inform them to not feed the deer and adhere to the speed limit (e.g. an "entrance station" at the Jct of Key deer Blvd and US Hwy 1, managed by volunteers). This Jct is currently a problem for traffic flow. Potential redesign of this Jct could include an "entrance station" aimed at visitors and a system that would let residents pass without delay.

c. Inspect the existing mitigation measures along US Hwy 1 for potential maintenance issues (e.g. fence repair issues).

Task 4: Provide a report summarizing the findings.

2. TRAFFIC CHARACTERISTICS

2.1. Introduction

In this chapter we describe the traffic characteristics of US Hwy 1 and other roads on Big Pine Key.

2.2. Annual Average Daily Traffic Volume (AADT)

In 2017 US Hwy 1 had an Annual Average Daily Traffic Volume (AADT) of 18,590-19,600 vehicles per day (FDOT, 2018) (Figure 15). The vast majority were passenger cars (92.2%) and 7.8% of the vehicles were trucks (single unit, combination trailer, and multi-trailer trucks combined) (FDOT, 2018). The secondary roads had much lower traffic volume, up to several thousands of vehicles per day. However, Key deer Blvd had relatively high traffic volume though near the shopping center; just over 10,000 vehicles per day.

Figure 15: Annual Average Daily Traffic (AADT) on US Hwy 1 and secondary roads on Big Pine Key in 2017 (FDOT, 2018).

2.3. Traffic Characteristics US Hwy 1

Traffic volume reduced between 2004 and 2010 leading up to and into an economic recession (Figure 16). However, traffic steadily increased again from 2010 onward (Figure 15).

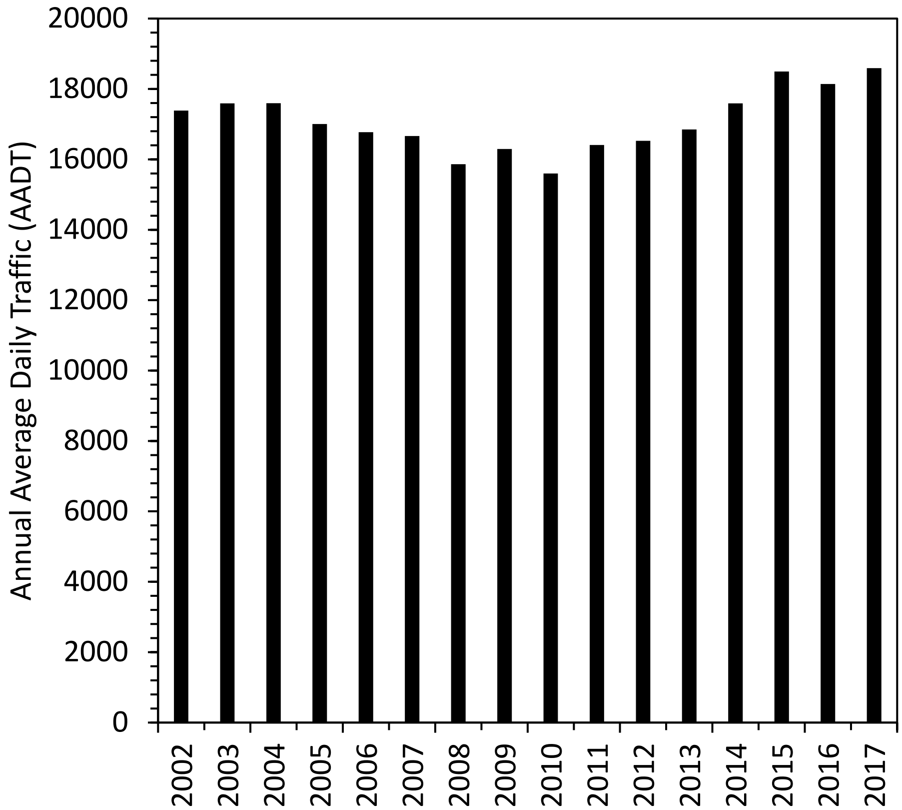

Figure 16: Annual Average Daily Traffic (AADT) on US Hwy 1, 0227 - SR-5/US-1,200' NE NORTH PINE CHANNEL BRG, MONROE CO (FDOT, 2018).

Traffic volume varied by month, though data for some months were not recorded (Figure 17). For the months that data were available for in 2017, traffic volume was highest during the winter (February, March).

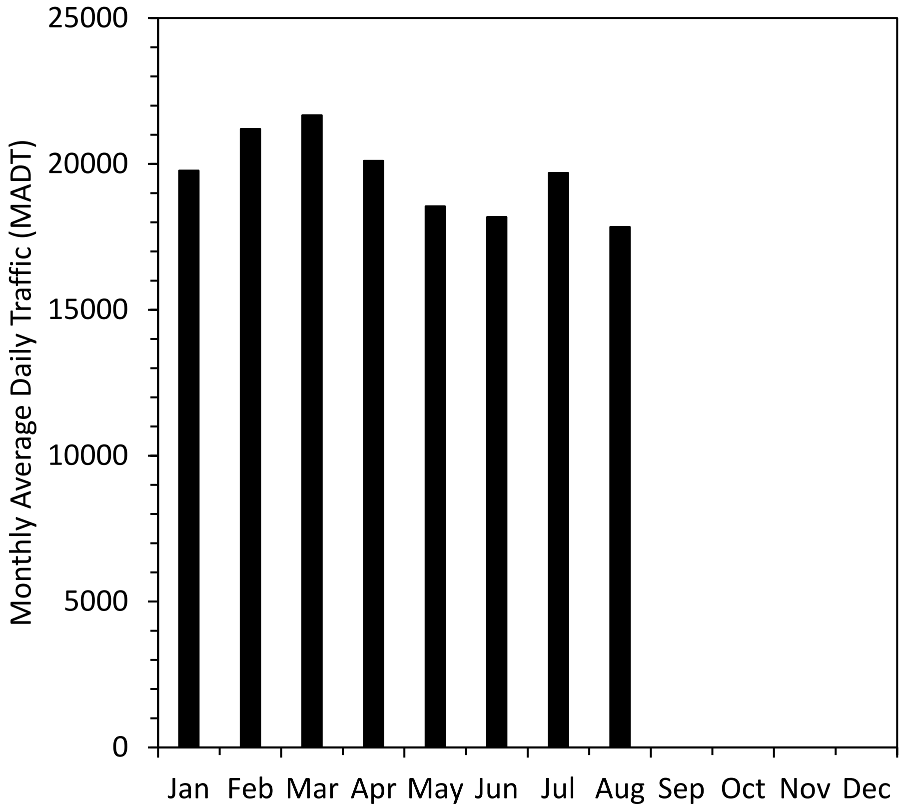

Figure 17: Monthly Average Daily Traffic (MADT) in 2017 on US Hwy 1, 0227 - SR-5/US-1,200' NE NORTH PINE CHANNEL BRG, MONROE CO (FDOT, 2018). No data available Sep through Dec 2017.

Traffic volume was highest during the daylight hours, both in February and in June 2017 (Figures 18, 19). However, traffic volume in the evenings during dusk and darkness remained relatively high until 10-11 pm.

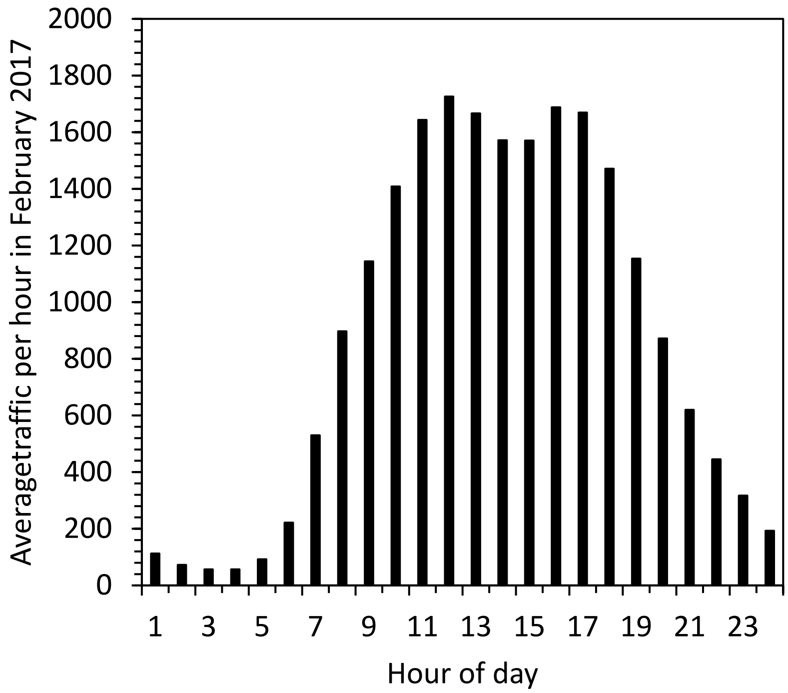

Figure 18: Traffic volume by hour of day in February 2017 on US Hwy 1, 0227 - SR-5/US-1,200' NE NORTH PINE CHANNEL BRG, MONROE CO (FDOT, 2018).

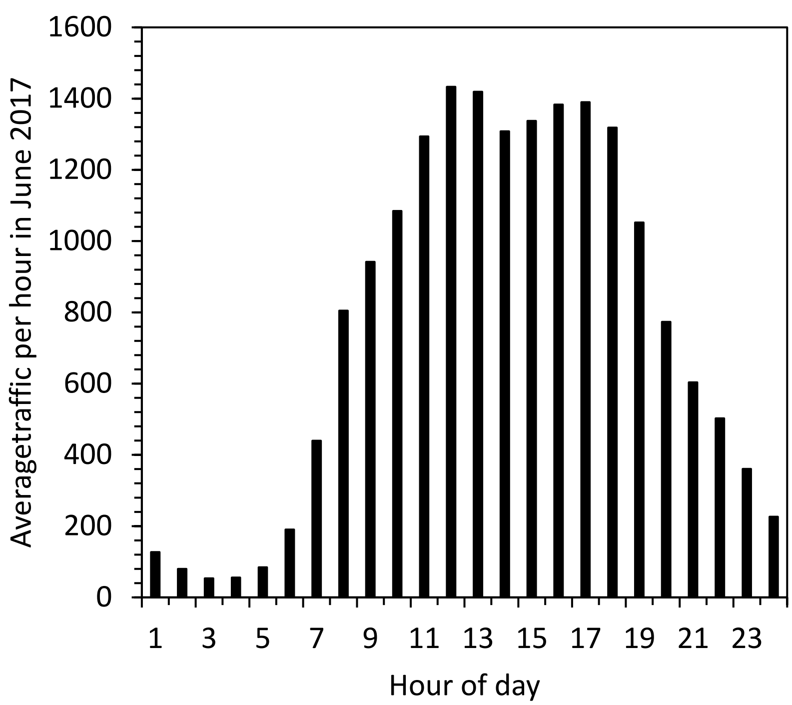

Figure 19: Traffic volume by hour of day in June 2017 on US Hwy 1, 0227 - SR-5/US-1,200' NE NORTH PINE CHANNEL BRG, MONROE CO (FDOT, 2018).

3. EXPLORATION OF THE KEY DEER MORTALITY DATA

3.1. Data Selection

We used the existing database on key deer mortalities between 1966 (first record 9 March 1966) through partway 2017 (last record 9 November 2017). The data were obtained 7 December 2017 through Kate G. Watts, Wildlife Biologist, United States Fish and Wildlife Service (USFWS Florida Keys NWR Complex), Big Pine Key, Florida. Note that the Key deer mortality data is collected opportunistically by FKNWRC and Florida Fish and Wildlife Conservation Commission law enforcement. Not every dead Key deer and cause of death is reported and recorded. This means that are inherent biases in the data; a road-killed Key deer is more likely to be recorded than a drowned Key deer, or a Key deer that died (e.g. from a disease) away from roads, trails, and people that can find and report the dead animal.

3.2. Known Mortalities and Mortality Causes

There were 4,753 recorded mortalities of Key deer (*Odocoileus virginianus clavium*) in the database. Overall, roadkill was the most common recorded mortality source (n=3,412, 71.8%) (Figure 20).

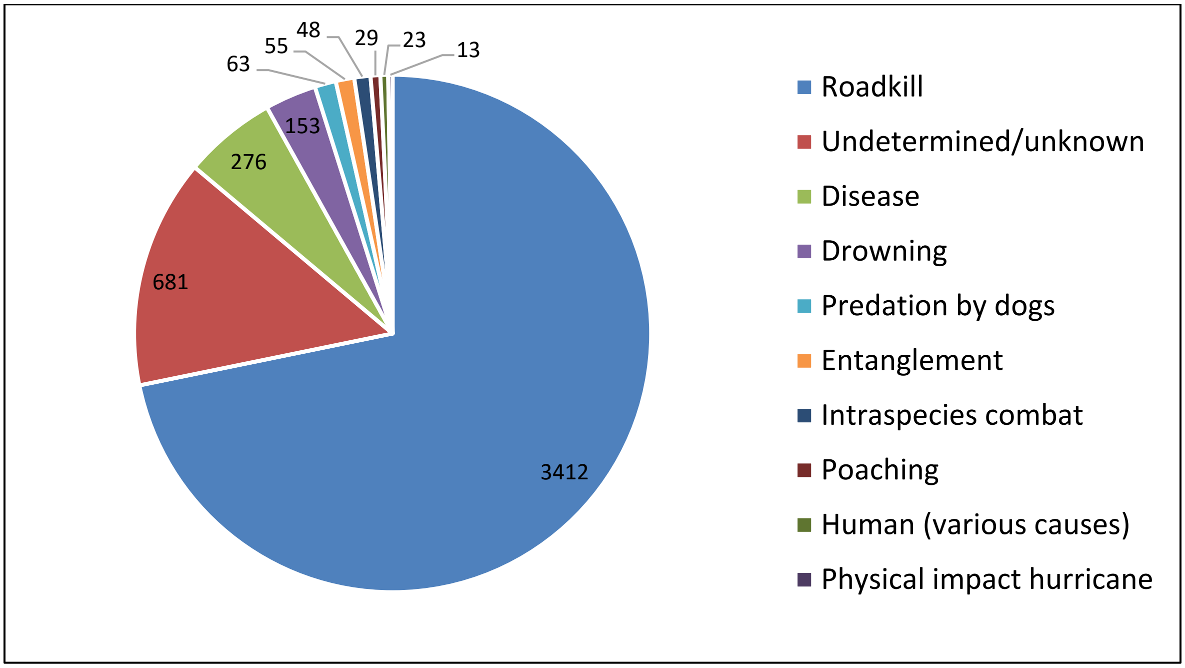

Figure 20: The number of recorded Key deer mortalities by mortality cause between 1966-2017.

We calculated the number of Key deer mortalities by cause of death by year (1966 through 2016) (Figure 21). Data from 2017 were excluded as the different causes of death have a seasonal influence and we did not have the mortality data for the full calendar year. Road mortality has been consistently the leading known source of mortality since record keeping began in 1966 (Figure 21). However, in 2016 a disease (screw worm infestation) resulted in mortality numbers similar to roadkill.

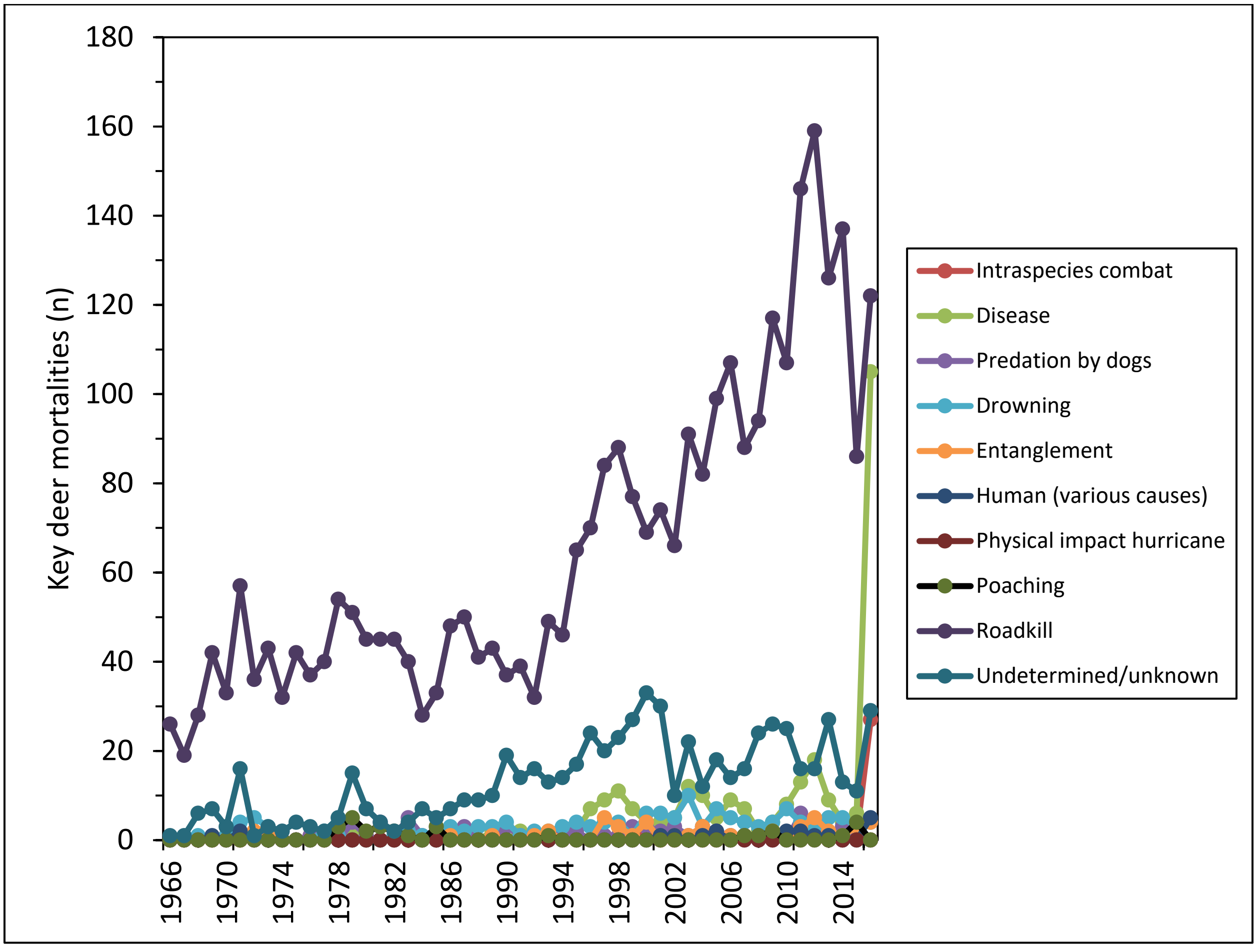

Figure 21: The number of recorded Key deer mortalities by year by mortality cause between 1966-2016.

We calculated the percentage of Key deer road mortalities out of all recorded Key deer mortalities for each year (1966-2016) (Figure 22). We then calculated the average percentage of Key deer road mortalities per year: 75.5% (SD=10.2). The drop in 2016 is because of the high numbers of deaths related to the screw worm infestation.

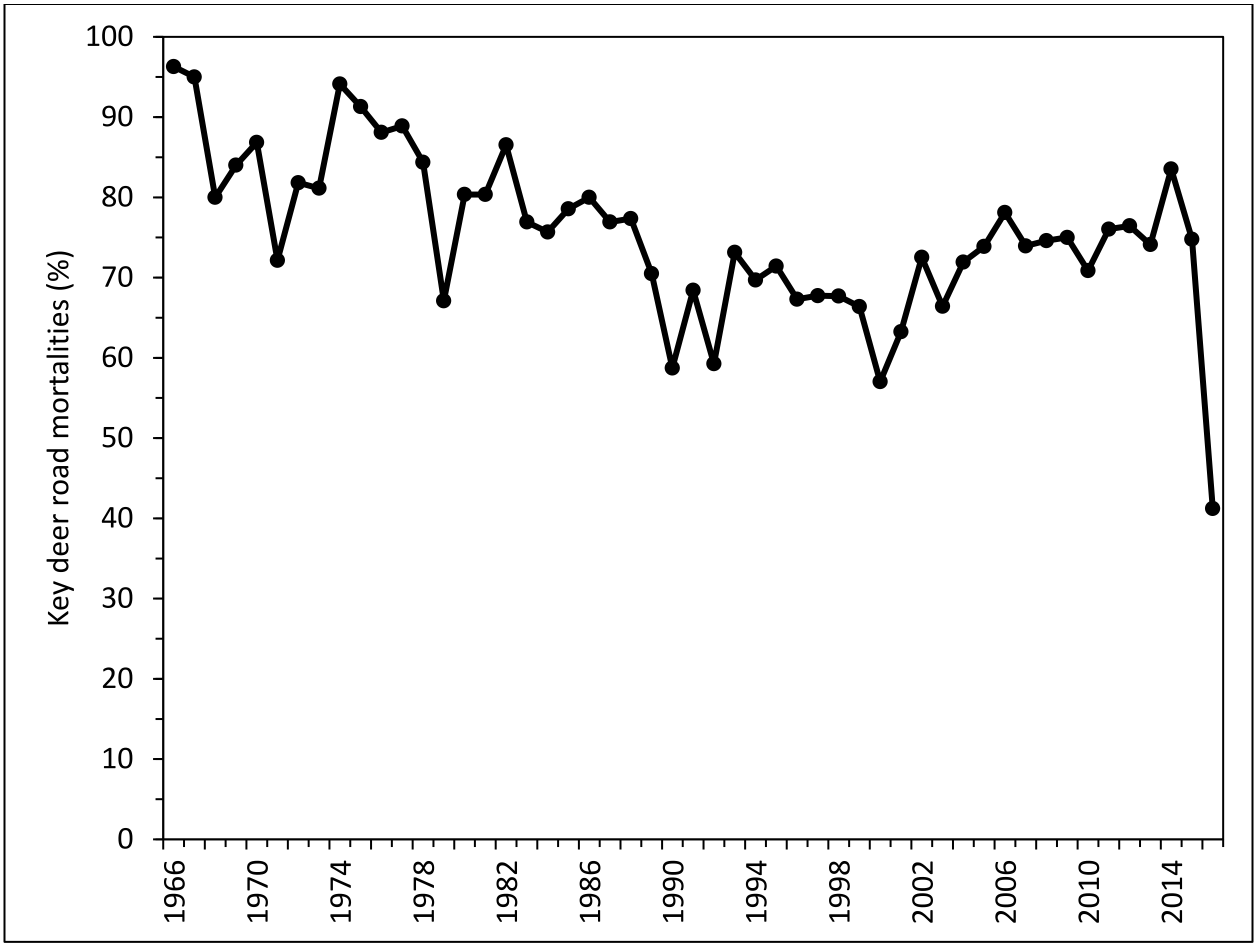

Figure 22: The percentage of Key deer road mortalities out of all recorded Key deer mortalities per year (1966-2016).

The number of road-killed Key deer varied by time of year (Figure 23). October through December with a peak in November, and May through August were the months with highest Key deer road mortality (for the years 2003 through 2016). These road-killed deer were predominantly male (55.7% male; 38.9% female, 5.5% unknown gender).

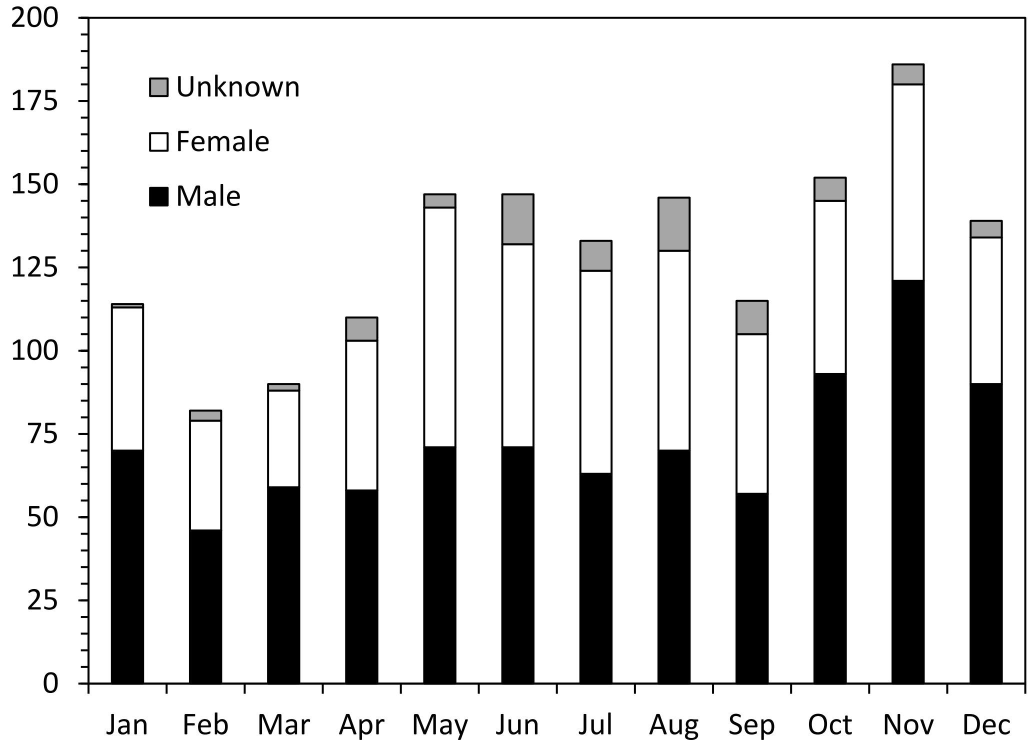

Figure 23: The number of road-killed deer per month by gender between 2003 through 2016, for all roads and islands.

4. REMAINING ROAD MORTALITY HOTSPOTS (2007-2016)

4.1. Introduction

In 2001 and 2002, the Key deer fence and underpasses were constructed along the eastern section of US Hwy 1 on Big Pine Key. In this chapter we investigate where the greatest concentration of hotspots was after mitigating the eastern section of US Hwy 1. The results show the locations where further efforts to reduce Key deer-vehicle collisions should be directed, should one choose to do so. Note that despite the ongoing road mortality, the Key deer population size has continued to grow and that the Key deer population is not reducing because of direct road mortality (Parker et al., 2011).

4.2. Methods

For the hotspot analysis, we only selected roadkill records of Key deer for the most recent 10-year period (2007 through 2016, n=1,182), regardless of where they occurred (both on and off Big Pine Key, both inside and outside the mitigated section of US Hwy 1). Using records of the most recent ten years seems to be a good balance between having recent data that identify current hotspots and having a sample size (number of individuals as well as years) that is likely to result in correctly identifying hotspots that are both current and robust. We then proceeded with conducting a hotspot analysis for these data.

We conducted a Kernel density analysis using ArcGIS 10.6.1 (ESRI, 2018a) for point features of Key Deer WVC locations using a 25 m cell size (82 ft x 82 ft). A 25 m cell size is relatively fine scale and accommodates for some spatial inaccuracies in GPS coordinates. The Kernel density analysis calculates the density of roadkills in a neighborhood around each cell and based on the quartic kernel function described in Silverman (1986). Consistent with Gomes et al. (2009) we set the neighborhood search radius at 500 m. On a straight road this basically means that Key deer roadkill that are up to about 0.3 mi (500 m) away are included in the density analyses for each cell.

To help interpret the results of the Kernel density analyses and identify hotspots we displayed the raster output using two different classifications methods that produced heat maps showing varying densities of Key deer WVCs. We used percentage breaks in 10% increments that represent areas of lowest (1-10%) densities to highest (91-100%) densities. We also created broader categories and an inversed scale using 5 percentage breaks (<5%, 5-24.9%, 25-49.9%, 50-74.9%, and 75-100%) that displays the areas with the highest densities of Key deer WVCs (<5%) to areas with the lowest densities (75-100%). We overlaid publicly-owned (county, state and federal) and privately-owned land on top of this hotspot map.

4.3. Results

Only the unmitigated western section of US Hwy 1 on Big Pine Key had road sections with Key deer roadkill concentrations in the highest Kernel density categories (41-100%; yellow, orange and red) (Figures 24, 25). There are two main hotspots; one on the west side of Big Pine Key (opposite of the canals (W. Cahill Ct.) until Deer run Tr.), and one at the west or north end of the wildlife fence (opposite of the St. Peter Catholic Church), extending further west till Cunningham Ln. Between the west end of Big Pine Key and the fence end (west or north fence end) there were 575 Key deer roadkill whereas there were only 25 roadkill in the fenced section of US Hwy 1.

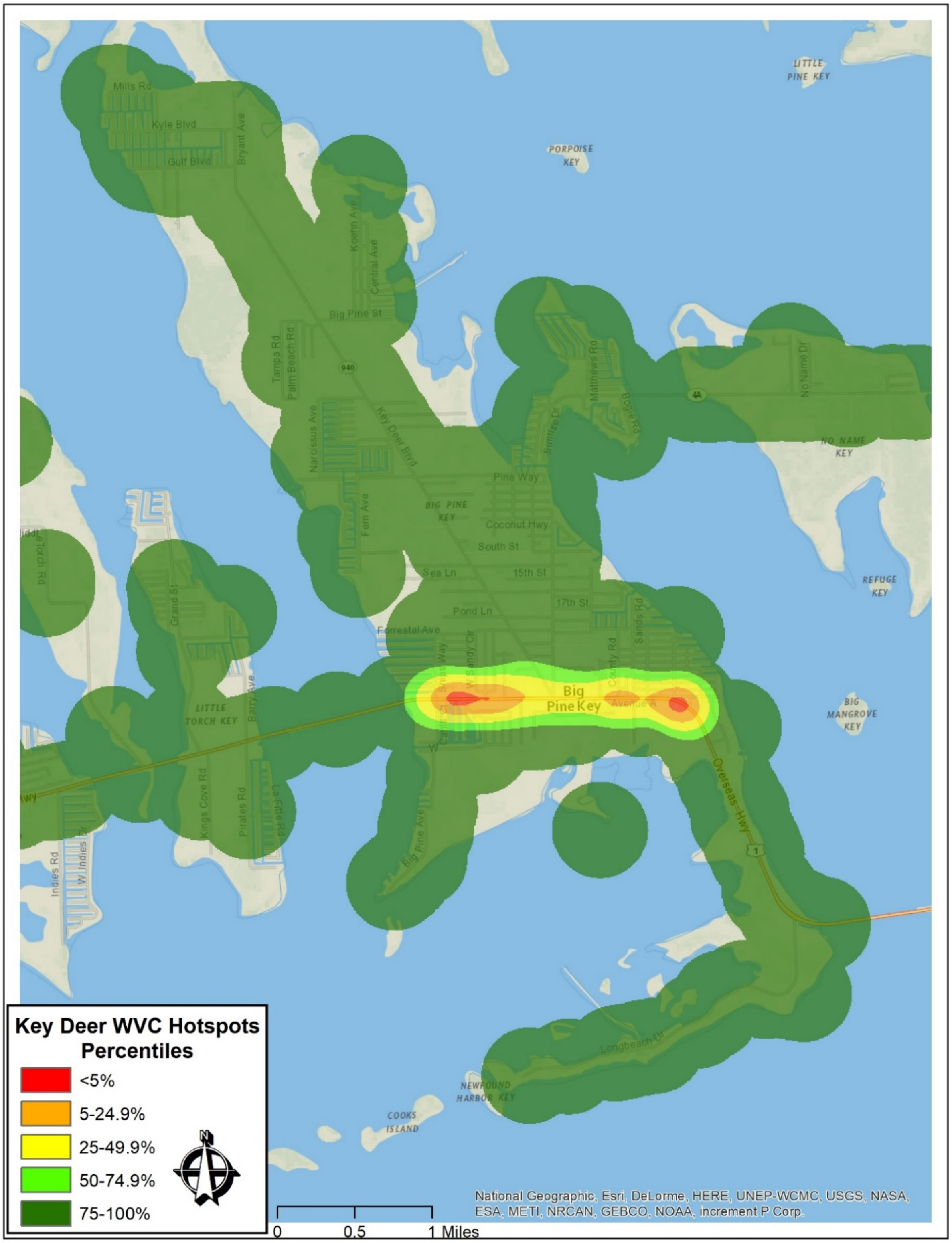

Figure 24: Kernel density hotspot map using percentiles for Key deer-vehicle collisions (2007 through 2016).

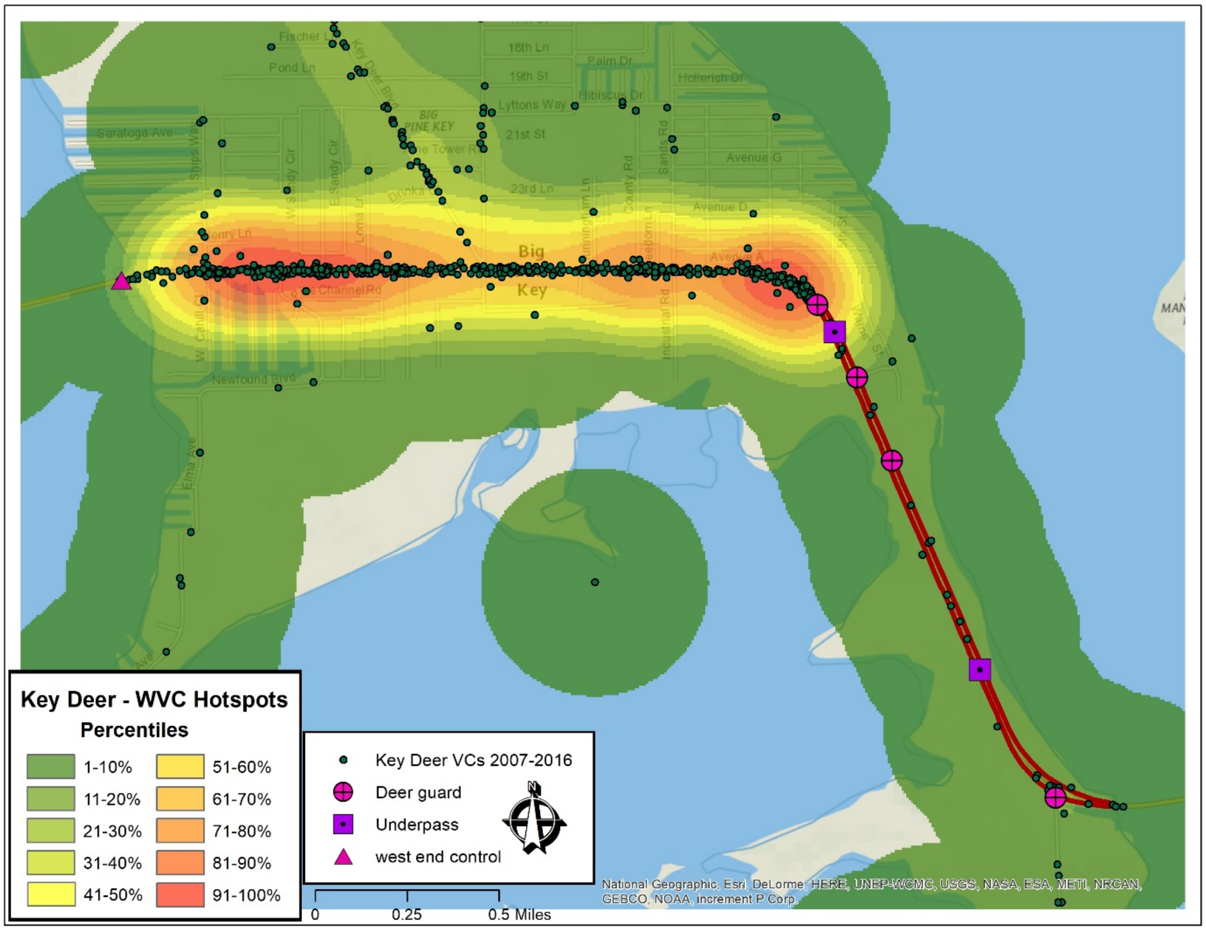

Figure 25: Kernel density hotspot map in 10% incremental categories for Key deer-vehicle collisions (2007 through 2016) along US Hwy 1 with the locations of Key deer-vehicle collisions plotted on top.

Figure 26 shows broader Kernel density percentage categories with public and private land ownership. The greatest concentrations of publicly owned land on either side of US Hwy 1 only partially align with the hotspots: around Pine Channel rd on the west side of Big Pine Key, and between Sands Rd and Wilder Rd towards the east side of the island (Figure 27).

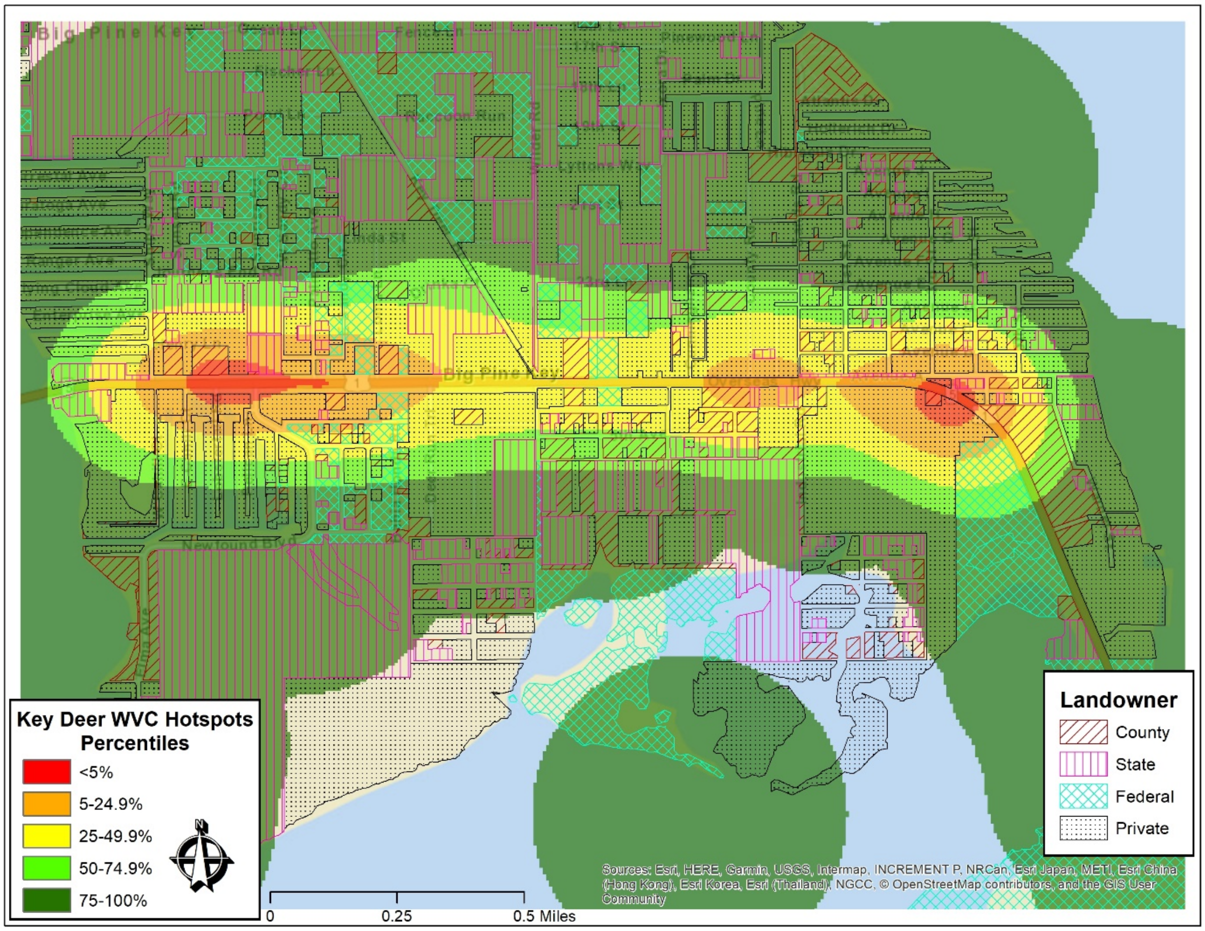

Figure 26: Landownership (county, state, federal, private) and Kernel density hotspot map (percentiles) for Key deer-vehicle collisions (2007 through 2016).

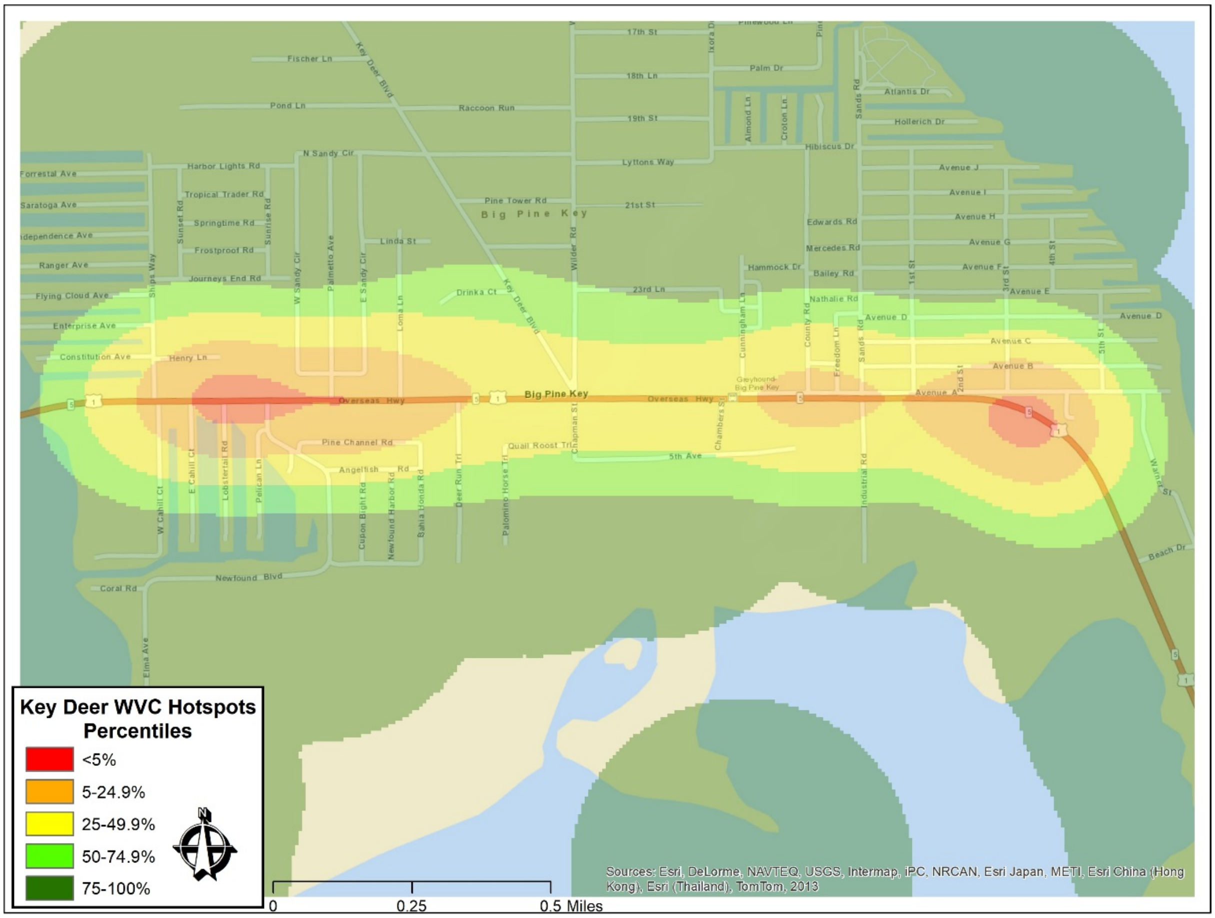

Figure 27: Kernel density hotspot map (percentiles) for Key deer-vehicle collisions (2007 through 2016) in relation to US Hwy 1 and the adjacent roads on Big Pine Key.

4.4. Discussion

If roadkill of Key deer is to be reduced further, the efforts should be concentrated on the unmitigated section of US Hwy 1. If this road section cannot be addressed in its entirety, the efforts should be especially directed to the west side of Big Pine Key (opposite of the canals (W. Cahill Ct.) until Deer run Tr.), and to the west or north end of the wildlife fence (opposite of the St. Peter Catholic Church), potentially extending further west till Cunningham Ln.

5. EFFECTIVENESS OF THE MITIGATION MEASURES IN REDUCING COLLISIONS

5.1. Introduction

In 2001 and 2002, the Key deer fence, underpasses, and deer guards were constructed along the eastern section of US Hwy 1 on Big Pine Key. In this chapter we investigate the effectiveness of the Key deer these measures in reducing Key deer-vehicle collisions.

5.2. Methods

5.2.1. Before-After-Control-Impact (BACI)

For the Before-After-Control-Impact (BACI) analysis, we only selected roadkill records of Key deer; 10 years before the implementation of the mitigation measures (1991 through 2000), and 14 years after the implementation of the mitigation measures (2003 through 2016). The mitigation measures were under construction in 2001 and 2002; hence these two years were excluded from the BACI analyses. The control was the unmitigated road section of US Hwy 1 (from the western/northern fence end until the west side of the island), and the impact was the mitigated road section US Hwy 1 (the fenced section on the eastern side of the island). Since there was some spatial imprecision in the original data, we included observations of road killed Key deer that were up to 50 m from either side of US Hwy 1.

For the BACI analysis, we calculated the number of Key deer roadkill records per mile for each calendar year for the control (unmitigated) and the impact (mitigated) road section. We calculated the BACI effect according to $(\mu_{control,after} - \mu_{control,before}) - (\mu_{impact,after} - \mu_{impact,before})$. In addition, the Key deer roadkills per mile per year were transformed (ln(x+0.1)) to make the count variable resemble a normal distribution. This allowed for the investigation of a potential interaction of the before-after and fenced-control parameters through an ANOVA. Should there be an effect of the treatment (i.e. the wildlife fences and the associated mitigation measures), the researchers expected the effect to result in fewer collisions rather than more. Hence our ANOVA was a one-sided test.

Parker et al. (2011) reported an increase in Key deer-vehicle collisions on the western unmitigated section of US Hwy 1 after the eastern section of US Hwy 1 was mitigated. This increase was attributed to the ongoing growth of the Key deer population and an increase in traffic volume (Parker et al., 2011). We explored this further by calculating the percentage of Key deer road mortalities in relation to the total population size in each calendar year (see Chapter 2). We calculated the percentages before (1991 through 2000) and after mitigation (2003 through 2014), and for the mitigated and the unmitigated section of US Hwy 1. However, Key deer population size estimates were only available for certain years (Table 1). In addition, the authors usually presented both a minimum and maximum population estimate. For our analyses we calculated and used the average population size. We fitted an exponential growth curve through the available population size estimates, allowing us to calculate the associated population size estimate for each calendar year. Note that we did not calculate population estimates after 2014, the last year the population was estimated based on field work, as we did not want to extrapolate beyond the data collection period (Table 1). We tested for potential differences between the percentage of road-killed Key deer of the total population size in the years before and after the mitigation measures were implemented (Kruskal-Wallis One-Way ANOVA on Ranks).

Table 1: Key population size estimates categories used for the BACI analyses.

Year	Minimum (n)	Maximum (n)	Average (min-max) (n)	Source
1940	?	50	50	Hardin *et al.* (1984)
1952	25	80	52.5	Dickson (1955)
1974	300	400	350	Klimstra *et al.* (1974)
1990	250	300	275	Seal *et al.* (1990)
2001	453	517	485	Lopez (2001)
2005	555	619	587	Roberts (2005)
2014	987	1012	999.5	Villanova *et al.* (2017)

5.2.2. Fence End

The control section was immediately adjacent to the fenced section and could thus potentially be influenced by a fence end effect. For example, after implementation of the fence, some Key deer may have walked alongside the fence until they reach the fence end. They could then cross the highway at-grade at the fence-end where they are exposed to potential collisions with vehicles. If this fence-end effect is present, it overestimates the collisions in the control section and, through the BACI analysis, it would then also overestimate the effectiveness of the fenced road section.

We conducted an optimal hot spot analysis (Getis-Ord Gi*) in ArcGIS 10.6.1 (ESRI, 2018b). This analysis identifies statistically significant spatial clusters of hotspots and cold spots of Key deer road mortalities. We selected all Key deer road mortality observations along US Hwy 1, both along the mitigated and unmitigated road section, before and after mitigation, up to 50 m from the highway. We then created a bounding polygon around the highway (50 m buffer from approximately the center of the highway) to allow for some spatial imprecision in the original data. We conducted separate analyses for the “before” (1991-2000; 331 observations, 5 outliers) and “after” data (2003-2016; 795 observations, 11 outliers, grid size 44 m). For the “before” data the optimal grid size was 43 m, and the optimal fixed distance band was 302 m. For the “after” data the optimal grid size was 44 m, and the optimal fixed distance band was 164 m.

5.3. Results

5.3.1. Before-After-Control-Impact (BACI)

Before the mitigation measures were implemented, the number of Key deer roadkill per mile was very similar between control and the impact road section (9.7 Key deer road-killed per mile per year for the control section and 8.8 for the impact road section (Figure 28). After the implementation of the mitigation measures Key deer roadkill decreased by 81.3% in the mitigated road section (to 1.7 Key deer road-killed per mile per year). After the implementation of the mitigation measures Key deer roadkill increased by 191.1% in the control road section (to 28.2 Key deer road-killed per mile per year). The BACI effect was 25.7. This means that, because of the implementation of the mitigation measures, and assuming that what happened in the control section was not influenced by what happened in the fenced section, there were 25.7 fewer road-killed Key deer per mile per year in the mitigated road section. In this context, the percentage reduction in Key deer-vehicle collisions in the mitigated road section was (25.7 / (25.70+1.66)) * 100 = 93.9%.

The interaction of the before-after and mitigated-control parameters was significant (one-sided ANOVA $F_{1,44}=69.88$, $P<0.001$). This meant that the effect of time (before-after) on the number of road-killed Key deer indeed depended on the treatment (wildlife fences, wildlife guards, and wildlife crossing structures vs. no wildlife mitigation measures).

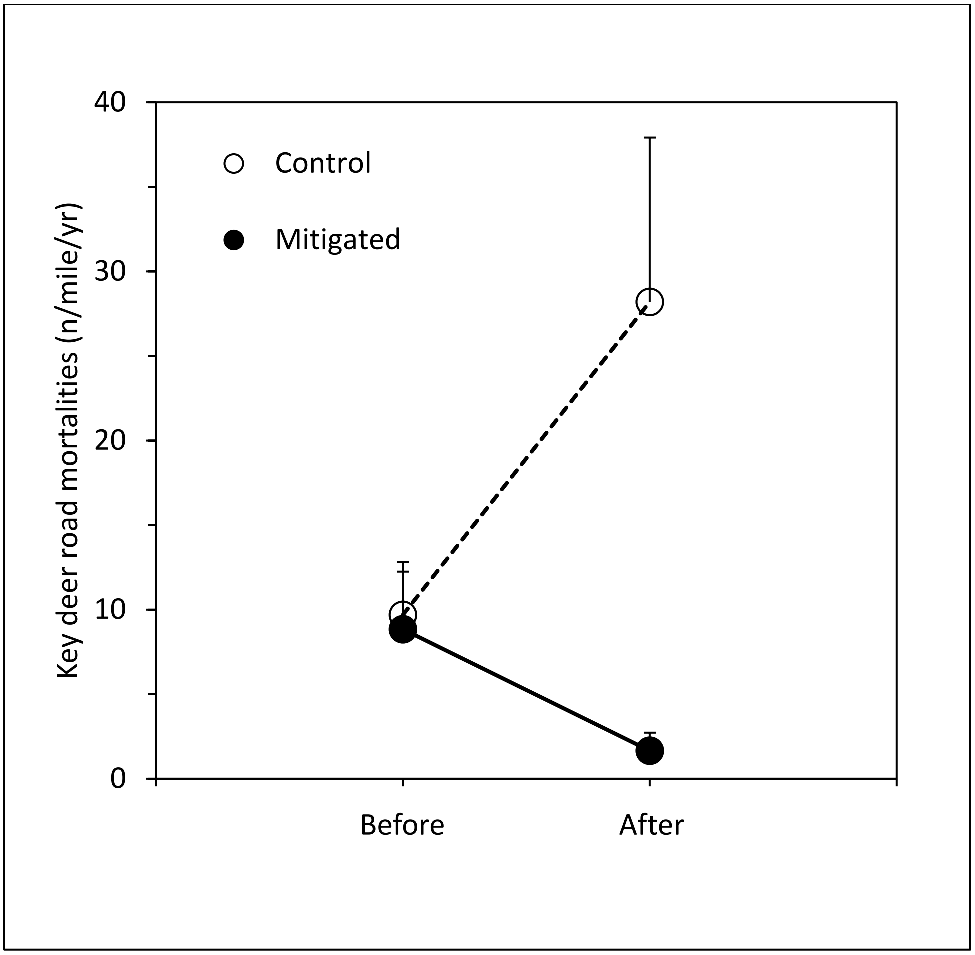

Figure 28: The average number of Key deer-vehicle collisions per mile per year and associated standard deviation reported from the unmitigated (control) and mitigated (impact) road section (with wildlife fences) before and after the mitigation measures were implemented.

We fitted an exponential growth curve through the available population size estimates (Figure 29) (R^2 =0.931). The curve allowed us to calculate the estimated deer population size for each calendar year before (1991 through 2000) and after mitigation (2003 through 2014).

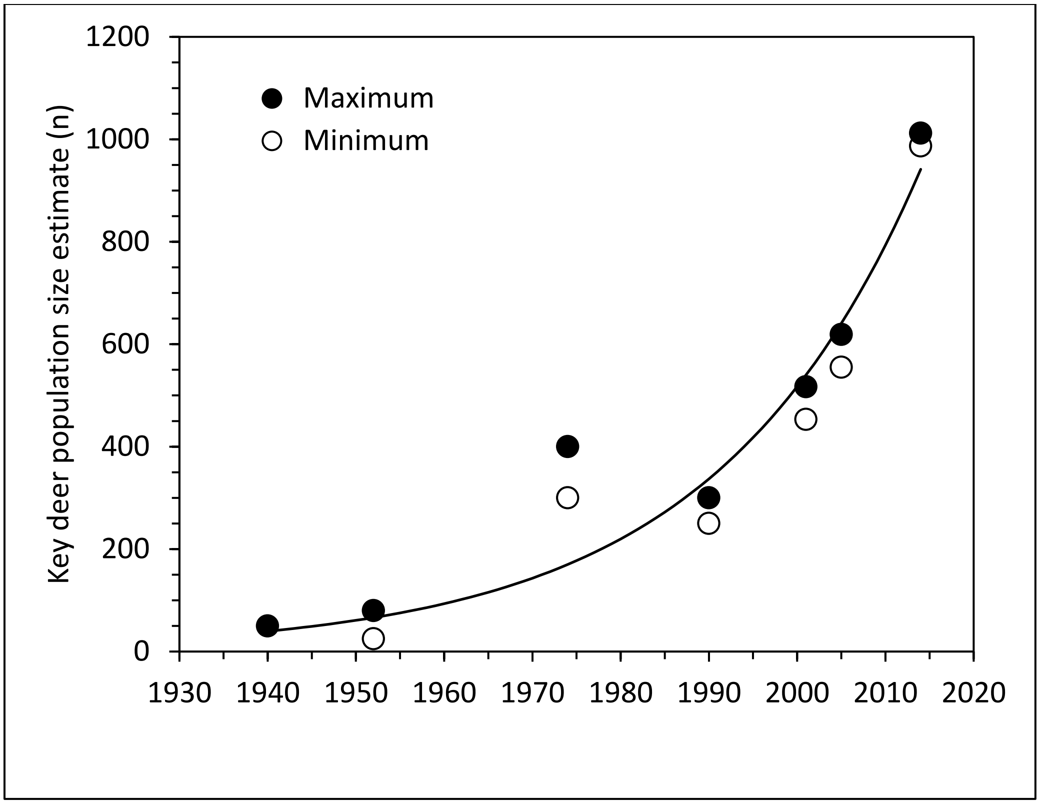

Figure 29: Estimated Key deer population size based on fitting an exponential growth curve ($y=e^{(0.04279*((year)-1853.976)}$) through data from the literature (see methods).

The percentage of road-killed Key deer of the total population size for all roads combined was similar before (average 14.2%, SD=3.2) and after (average 14.9%, SD=1.8) the fence and associated mitigation measures were implemented along the eastern section of US Hwy 1 (Kruskal-Wallis One-Way ANOVA on Ranks, Chi^2=0.109, P=0.742) (Figure 30). The percentage of road-killed Key deer of the total population size for US Hwy 1 on Big Pine Key was also similar before (7.6%, SD=2.1) and after (7.5%, SD=1.8) mitigation (Chi^2=0.017, P=0.895). However, there was a substantial drop in the mitigated section before (3.3%, SD=1.2) and after (0.3%, SD=0.2) mitigation (Chi^2=15.652, P<0.001). At the same time, there was a substantial increase in the unmitigated section before (4.3%, SD=1.1) and after (7.2%, SD=1.7) mitigation (Chi^2=14.126, P<0.001).

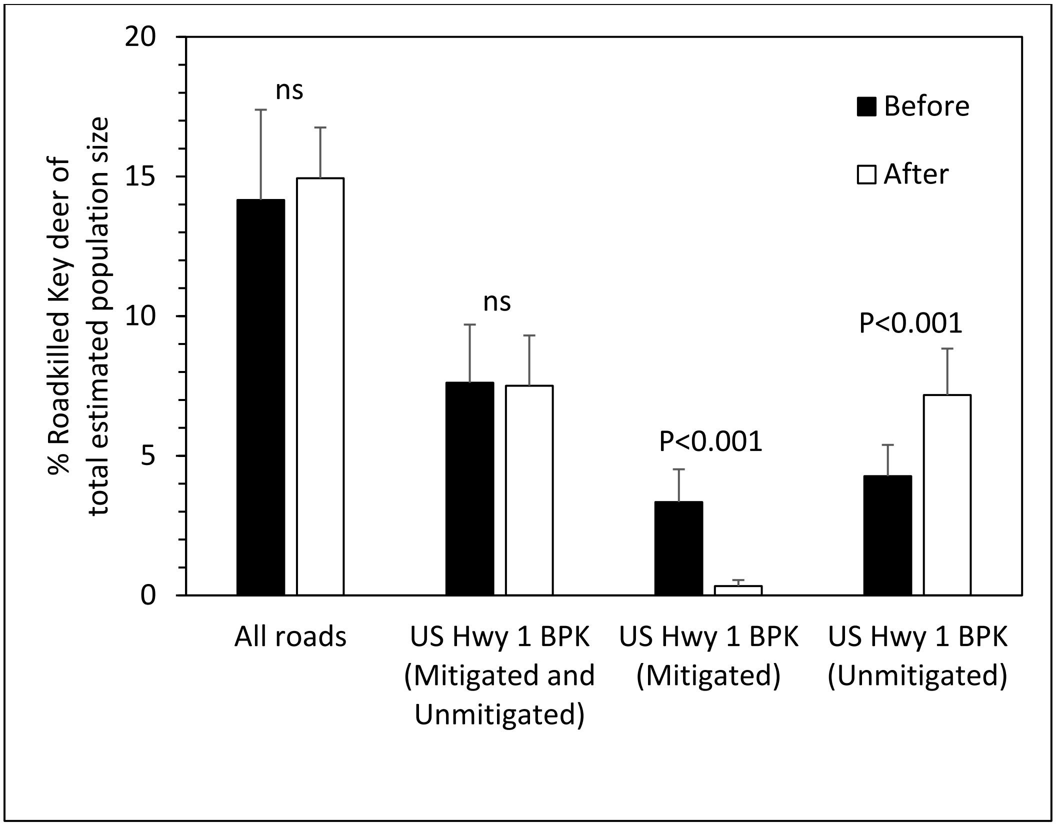

Figure 30: The average percentage and associated standard deviations of road-killed Key deer of the total estimated population size in the years before and after implementation of the mitigation measures along the eastern section of US Hwy 1 on Big Pine Key (BPK).

5.3.2. Fence End

Before the eastern section of US Hwy 1 was mitigated, there was a significant concentration of Key deer-vehicle collisions at the eastern edge of Big Pine Key (Figure 31). This hotspot disappeared after the implementation of the mitigation measures, and almost the entire length of the mitigated road section turned into a significant cold spot (Figure 32). However, after mitigation, a significant hotspot appeared at the western fence end, extending for about 300 m (984 ft). Other hotspots were present further west along the unmitigated section of US Hwy 1.

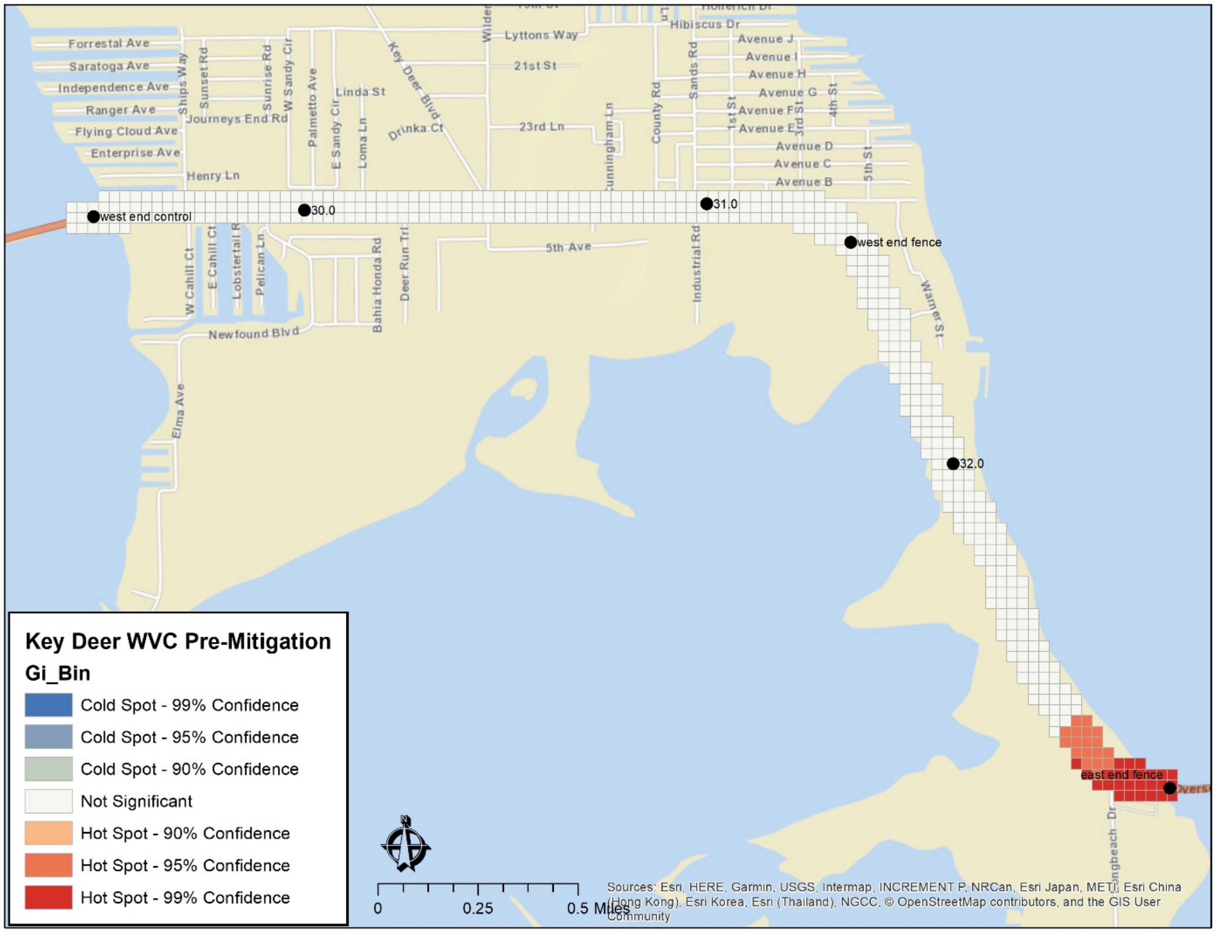

Figure 31: Significant hotspots and cold spots for Key deer-vehicle collisions along US Hwy 1 before mitigation (1991-2000). Numbers represent the mile reference posts.

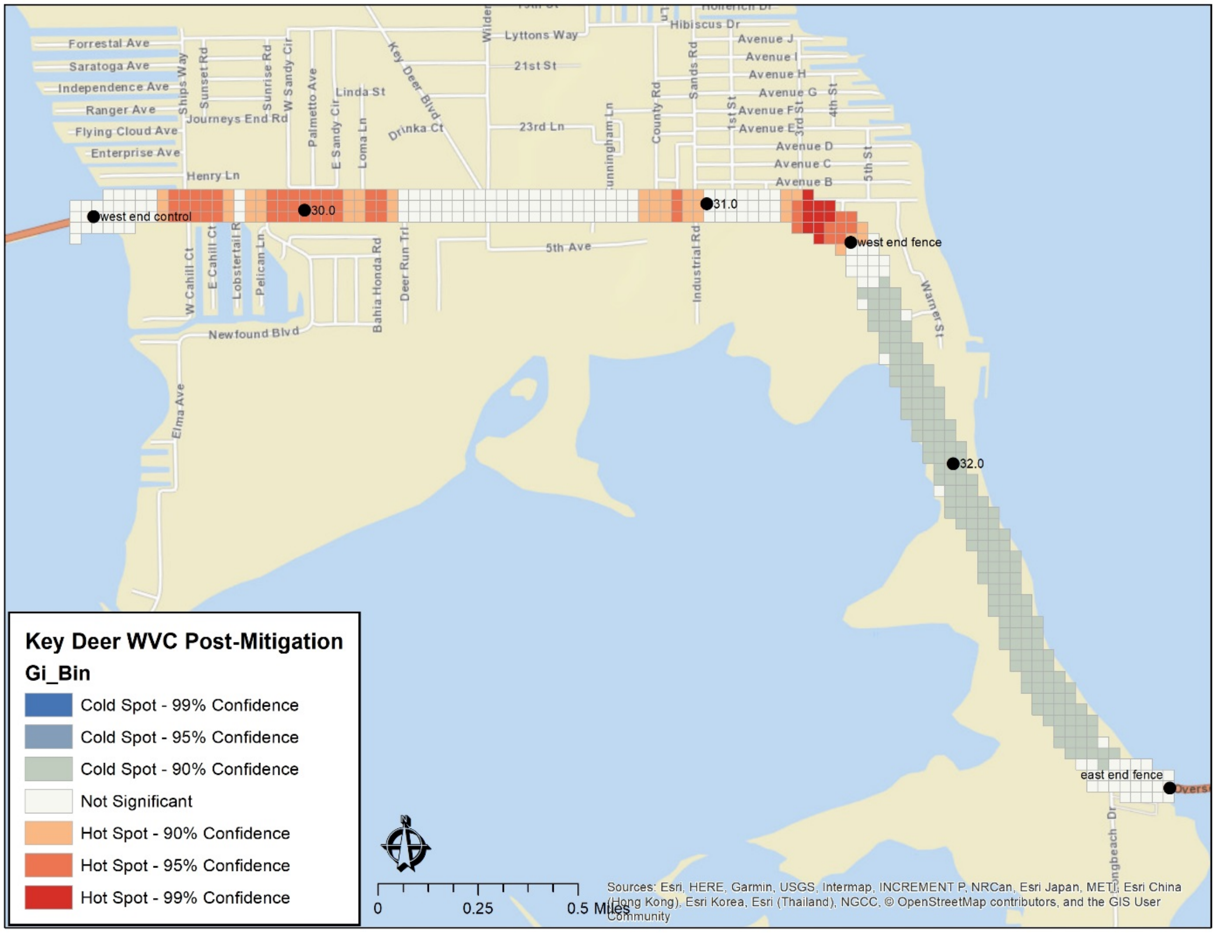

Figure 32: Significant hotspots and cold spots for Key deer-vehicle collisions along US Hwy 1 after mitigation (2003-2016). Numbers represent the mile reference posts.

5.4. Discussion

Based on the Before-After Control-Impact analysis, the wildlife fence and associated mitigation measures along the eastern section of US Hwy 1 on Big Pine Key were highly effective (93.9%) in reducing Key deer-vehicle collisions along that road section. However, the reduction in Key deer road mortality in the fenced section was accompanied by an increase in collisions in the unmitigated section of US Hwy 1, and the total number of roadkilled deer continued to increase. When corrected for the population size, Key deer road mortality was similar before and after highway mitigation for all roads combined as well as US Hwy 1 (mitigated and unmitigated section combined). Similar to the absolute numbers, the percentage of roadkilled Key deer in relation to the population size sharply decreased in the mitigated section of US Hwy 1 but substantially increased in the unmitigated section of US Hwy 1. Thus the overall Key deer road mortality on US Hwy 1 was not reduced; it was moved from the mitigated section to the unmitigated section of US Hwy 1. After mitigation, a significant hotspot of Key deer-vehicle collisions appeared at the west/north fence end of the mitigated section of US Hwy 1, likely as a result of some Key deer following the fence and crossing at-grade in higher than average numbers at the fence end. Other significant Key deer-vehicle collision hotspots after mitigation occurred furter west along the unmitigated highway section on Big Pine Key.

The BACI approach estimated that the mitigation measures were highly effective (93.9%) in reducing Key deer-vehicle collisions in the fenced section of US Hwy 1. However, the BACI approach assumes that the number of collisions in the control section is not influenced by the fenced section. But given the significant fence end effect extending into the control section, we know that the control section is at least partially influenced by the fenced section. If the effectiveness of the fenced road section is calculated based on a simple Before-After approach (excluding a correction for the control section), the measures reduced Key deer roadkill by 81.3% in the mitigated road section. Note that the downside of a Before-After approach is that it does not correct for the increase in Key deer population size and this leads to an underestimation of the effectiveness of the mitigation measures in reducing Key deer-vehicle collisions. Nonetheless, the mitigation measures were at least 81.3% effective in reducing Key deer-vehicle collisions in the fenced road section.

5.5. Management Implications

The wildlife fence and associated measures were highly effective in reducing Key deer-vehicle collisions on the fenced section of US Hwy 1. However, in order to reduce the overal number of Key deer-vehicle collisions along US Hwy 1, the entire section of US Hwy 1 on Big Pine Key needs to be mitigated. Ideally, the wildlife fence should be extended to the western side of Big Pine Key with additional safe crossing opportunities for Key deer and other wildlife species. However, the secion of US Hwy 1 that is currently still unfenced has many buildings and access roads to business and residences. This means that there are many competing interests; implementing mitigation measures that are effective in reducing Key deer-vehicle collisions and that also provide safe crossing opportunities for Key deer and other wildlife species, will affect other interests on and along US Hwy 1. The next chapter summarizes the pros and cons of different types and combinations of mitigation measures for the unfenced section of US Hwy 1.

It is important to bear in mind that the overall number of collisions is just one parameter associated with the presence of the mitigation measures along the eastern section of US Hwy 1. For example, eventhough the overall number of key-deer vehicle collsions along US Hwy 1 was not reduced after mitigation, the remaining collisions mostly occur along the section where the design speed and surroundings (side roads, entrances to businesses, pedestrians, cyclists) may encourage drivers to have lower operating speed and pay more attention to their surroundings compared to the fenced portion of US Hwy 1 (very few side roads, no buildings adjacent to the highway, wide right-of-way). Thus there may be a lower likelihood of human injuries and human fatalities when hitting a key deer in the western section of US Hwy 1. Another benefit of the mitigation measures is that the mitigated section of US Hwy 1 also provides safe crossing opportunities for Key deer through the underpasses (Braden et al., 2008; Parker et al., 2011).

6. MORTALITY REDUCTION OPPORTUNITIES ALONG US HWY 1

6.1. Considerations

In this chapter, we explore several opportunities aimed at reducing Key deer-vehicle collisions along US Hwy 1. Rather than suggesting one option, we summarize the pros and cons of each approach. The options described in this chapter are not endorsed by any organization and they have no planning status. We recognize that not all options described below are realistic. The opportunities described below are only meant as a free exploration of the pros and cons of a wide variety of options. The pros and cons include perspectives related to human safety, access for residents and clients of businesses, and Key deer conservation. Note that potential action can only be taken in collaboration with other stakeholders, including the community.

6.2. Strategy 0: No Action

This strategy is a continuation of the status quo and does not include any new opportunities along US Hwy 1.

Pros	Cons
No changes, restrictions or difficulties in accessing and leaving US Hwy 1 for residents, businesses, and clients.	**No further Key deer-vehicle collision reduction**; accept between 90-160 Key deer road mortalities every year in total, including the associated impacts to human safety. Note that the unfenced western section of US Hwy 1 had an average of 54.1 (SD = 18.7) Key deer road mortalities per year (28.2 per mile per year, SD = 9.7) between 2003 through 2016.
Current and future road mortality could be seen as a factor that helps reduce population growth and helps control the population size of Key deer as the population is believed to be at, near, or over carrying capacity based on the available habitat. Annual road mortality is 90-160 individuals per year. Based on an estimated key deer population size of 1,000 individuals, road mortality is 9-16% of the population per year. Population growth is estimated at 3.5% annually (Personal communication Kristie Killam USFWS/FKNWRC).	

6.3. Strategy 1: Addressing Collisions at the Fence End Only

Simply lengthening the existing fence and relocating the deer guard at the fence end may move the collisions to the new fence end rather than substantially reduce collisions. Therefore, we do not suggest extending the fence in the right-of-way a few hundred yards further into the curve. Instead, we suggest a combination of improved highway and right-of-way lighting and speed management, e.g. through speed bumps (Figure 33, 34, 35).

While it seems intuitive that highway lighting can improve the visibility of large mammals to drivers, the effectiveness of highway lighting is unclear at best (Reed & Woodard, 1981; McDonald 1991). Some animals may already be on the road when a vehicle approaches, and these animals can be made more visible to drivers. But animals that are running towards the road when a vehicle is approaching may not be more visible to the driver if the lights are only present along the highway. Nonetheless, in combination with other measures such as a lower design speed aimed at reducing vehicle operating speed, highway lighting may contribute to fewer large mammal-vehicle collisions (Figure 33, 34). Lighting should be directed to the ground and light pollution upwards to the sky should be minimized.

We also suggest considering a lower design speed of the highway in the area around the fence end (Figure 33, 35). Speed bumps can help reduce the operating speed of the vehicle, e.g. to 35 MPH (the current posted night time speed limit). Reducing operating speed through speed bumps and potentially also separating the two lanes to reduce design speed further can reduce collisions with key deer (Figure 35). A vehicle operating speed of about 40 mi/h does allow about half the drivers to stop in time for a very large mammal (moose) on the highway in the dark (Huijser et al., 2017). Measures that help enforce the current posted night time speed limit of 35 MPH (night) can result in fewer collisions with Key deer. For example, reducing vehicle operating speed from 45 MPH (current posted speed limit during the day) to 35 MPH (current posted speed limit during the night) results in a potential reduction in stopping distance of 30.1 m (98.6 ft) from 89.4 m (293.3 ft) to 59.3 m (194.6 ft) (Huijser et al., 2017). Lower operating speed results in even shorter stopping distances, of course.

Note that there are also negative side effects of highway lighting. Highway lighting may increase the barrier effect of the highway with fewer deer approaching and crossing the highway. Several terrestrial mammal species reduce their activity with light, independent of light color, and deer use crossing structures less when the adjacent road sections are lighted. (Spoelstra et al., 2015; Bliss-Ketchum et al., 2016).

Given the high traffic volume, we do not suggest implementing an animal detection system along US Hwy 1 as sudden braking in response to an activated warning sign may result in rear-end crashes (Huijser et al., 2015a).

Figure 33: Example of potential future mitigation measures associated with strategy 1.

Figure 34: Street lighting to increase the visibility of moose to drivers, Norway.

Figure 35: At-grade crossing opportunity for large mammals at a gap in the fence with speed bumps, The Netherlands.

Pros	**Cons**
No changes, restrictions or difficulties in accessing and leaving US Hwy 1 for residents, businesses, and clients.	**No further Key deer-vehicle collision reduction further west, beyond the curve adjacent to the fence end.**
Potential reduction in collisions near the fence end. Extent of this reduction is unknown.	

6.4. Strategy 2: Fence the Remaining Section of US Hwy 1 Between the Highway and the Adjacent Buildings (Businesses, Residences)

This strategy would extend the existing Key deer fence until the west side of Big Pine Key with wildlife or deer guards at selected access points for side roads and businesses (Figure 36). The fence would be installed between US Hwy 1 and the adjacent buildings (businesses, houses). This also means that frontage roads would have to be present on the safe side of the wildlife fence to reach the businesses and residences that do not have an access point with a deer guard in front of their property. Note: The authors of this report do NOT RECOMMEND wildlife fences without safe crossing opportunities for wildlife.

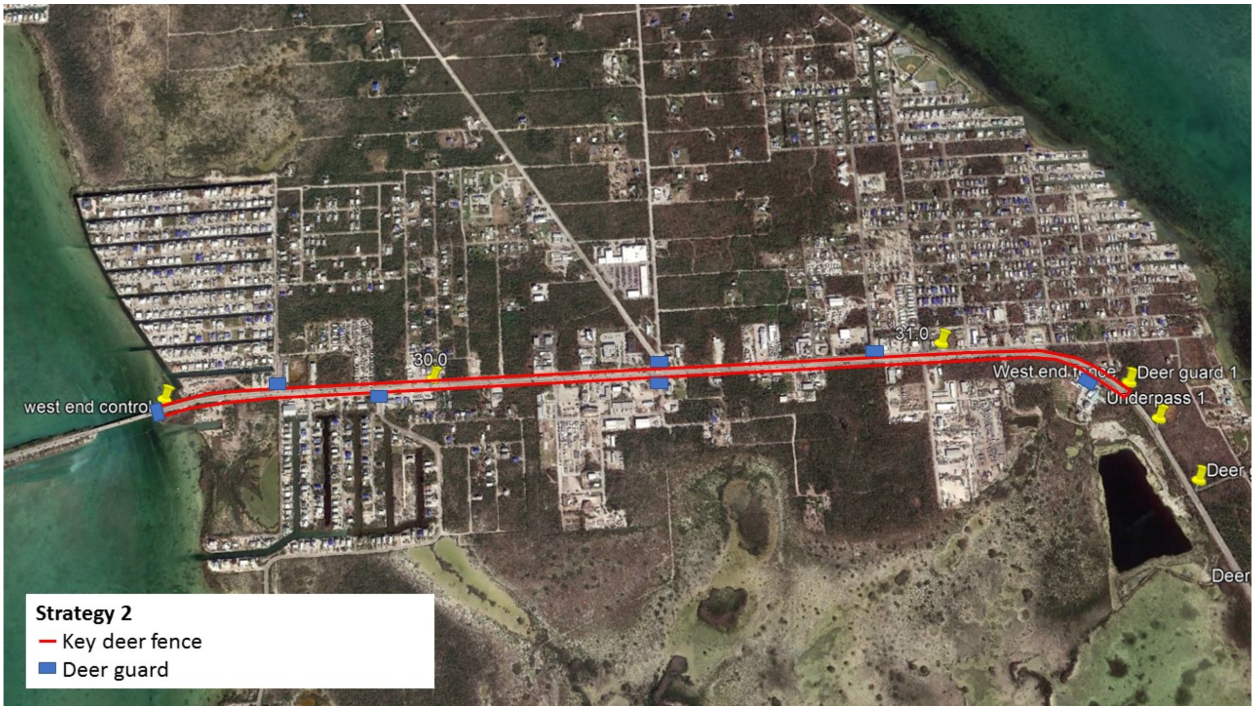

Figure 36: Example of potential future mitigation measures associated with strategy 2.

Pros	Cons
Assuming the effectiveness of the mitigation measures along the western section of US Hwy 1 will be similar to that of the mitigation measures along the eastern section of US Hwy 1, we can expect **93.9% reduction in Key deer-vehicle collisions along the western section of US Hwy 1.** This would reduce the number of Key deer road mortalities and associated impacts to human safety in the western section of US Hwy 1 from 54.1 (SD = 18.7) to 3.3 per year (50.1 fewer Key deer road mortalities per year). Through fencing the western portion of US Hwy 1, the **total number of Key deer-vehicle collisions would be reduced by 50.1 from 90-160 per year to 40-110 per year**.	**An increase in the barrier effect of US Hwy 1 could effectively split the Key deer population in two, reduce access to habitat for Key deer, and thus reduce the carrying capacity, and Key deer population size and population viability.** The western section of US Hwy 1 becomes (nearly) impermeable to Key deer, and the only way to cross US Hwy 1 and move between the south and the north side of the island is through the 2 existing underpasses along the eastern portion of US Hwy 1. Without dispersal from the area north of US Hwy 1, the Key deer population south of Highway 1 will likely drop below 25 individuals within 20 years (Harveson et al., 2004). Note: there will likely be some Key deer that will still walk across the wildlife guards to

	move across US Hwy 1, but these wildlife guards are estimated to be 99.5% effective in stopping Key deer (Peterson et al., 2003). In addition, there is always a possibility that some Key deer will swim to move between the north and south side of the island.
Reduced access points for people could potentially result in a situation that allows for **higher posted speed limits and better traffic flow on US Hwy 1**, also during hurricane evacuation.	**Reduction of road mortality may lead to faster population growth and further increase in population size of Key deer above the carrying capacity of the habitat** and issues associated with overpopulation (e.g. starvation, disease).
	Reduced access to businesses and residences and associated negative economic impact.
	Visual impact of the wildlife fence. The view of business and residences along US Hwy 1 would be obstructed by the fence.
	Reconstruction or construction of frontage roads may be required to reach the businesses and residences that do not have an access point with a deer guard in front of their property.
	New frontage roads or higher use of frontage roads may increase Key deer road mortality, partially reducing the benefit of fencing the main highway.

6.5. Strategy 3: Fence the Remaining Section of US Hwy 1 Behind the First Row (or Block or Several Blocks) of Buildings (Businesses, Residences).

This strategy would extend the existing Key deer fence until the west side of Big Pine Key, but the fence would be placed BEHIND the businesses and residences adjacent to US Hwy 1 (Figure 37). Note that the fence could also be placed one or several blocks away from US Hwy 1 to include residential areas; there is a wide range of possible configurations. Access for people through the fence (all modes of transportation) would be limited to certain main side roads off US Hwy 1 that would have a wildlife guard installed. This strategy would effectively include businesses and residences adjacent to US Hwy 1 in the fenced road corridor which would be inaccessible to Key deer. Note: The authors of this report do NOT RECOMMEND wildlife fences without safe crossing opportunities for wildlife.

Figure 37: Example of potential future mitigation measures associated with strategy 3.

Pros	Cons
Assuming the effectiveness of the mitigation measures along the western section of US Hwy 1 will be similar to that of the mitigation measures along the eastern section of US Hwy 1, we can expect **93.9% reduction in Key deer-vehicle collisions along the western section of US Hwy 1.** This would reduce the number of Key deer road mortalities and associated impacts to human safety in the western section of US Hwy 1 from 54.1 (SD = 18.7) to 3.3 per year (50.1 fewer Key deer road mortalities per year). Through fencing the western portion of US Hwy 1, the **total number of Key deer-vehicle collisions would be reduced by 50.1 from 90-160 per year to 40-110 per year**.	**An increase in the barrier effect of US Hwy 1 could effectively split the Key deer population in two, reduce access to habitat for Key deer, and thus reduce the carrying capacity, and Key deer population size and population viability.** The western section of US Hwy 1 becomes (nearly) impermeable to Key deer, and the only way to cross US Hwy 1 and move between the south and the north side of the island is through the 2 existing underpasses along the eastern portion of US Hwy 1. Without dispersal from the area north of US Hwy 1, the Key deer population south of Highway 1 will likely drop below 25 individuals within 20 years (Harveson et al., 2004). Note: there will likely be some Key deer that will still walk across the wildlife guards to move across US Hwy 1, but these wildlife guards are estimated to be 99.5% effective in

	stopping Key deer (Peterson et al., 2003). In addition, there is always a possibility that some Key deer will swim to move between the north and south side of the island.
Reduced human-wildlife conflict and improved wildness of key deer (reduced access to unnatural foods (non-native species in yards, hand-outs) through the exclusion of the area immediately adjacent to the highway (Peterson et al., 2005).	**Reduction of road mortality may lead to faster population growth and further increase in population size of Key deer above the carrying capacity of the habitat** and issues associated with overpopulation (e.g. starvation, disease).
Compared to strategy 2, access to businesses and residences along US Hwy 1 remains (largely) unhindered.	The area in between the fences is no longer accessible to Key deer. **The reduction in accessible habitat for the Key deer reduces the carrying capacity for Key deer and can result in a smaller population size.**
Compared to strategy 2, the visual impact of the wildlife fence and the wildlife fence hindering the view of businesses along US Hwy 1 is much reduced as the fence is largely behind the buildings that are adjacent to the highway.	

6.6. Strategy 4: Combine Wildlife Fences (Strategy 3) with Safe Crossing Opportunities for Key Deer: Animal Detection Systems

This strategy combines Strategy 3 with animal detection systems designed to detect Key deer and activate real time warning signs that encourage drivers to be more alert, slow down, or a combination of the two (Huijser et al., 2015a) (Figure 38). Animal detection systems can reduce collisions with large mammals, but the range of effectiveness is very wide (33-97%; Huijser et al., 2015a), and potentially much lower than for long sections of wildlife fences in combination with underpasses or overpasses (Huijser et al., 2016). In addition, the Average Annual Daily Traffic (AADT) for US Hwy 1 on Big Pine Key was about 18,000 in 2016 (KBP Consulting, Inc., 2017). This is on the high side for animal detection systems (Huijser et al., 2015a;b) and higher traffic volumes during peak tourist seasons are even less suitable for animal detection systems. Because the probability of rear-end collisions increases with higher traffic volumes after sudden braking, animal detection systems are typically not installed along busy highways. Most animal detection systems are installed along roads with a traffic volume of around 10,000 vehicles per day (Huijser et al., 2015b). In addition, because the animals have been guided to cross the highway at the animal detection system(s) and the warning signs would encourage drivers to suddenly reduce their speed, there may be liability issues in case of collisions. Also note that most animal detection system projects fail because of technological or management problems (Huijser et al., 2015). The examples of the locations for animal detection systems (Figure 38) are indicative and based on a combination of current hotspots of collisions with Key deer and remaining (semi) natural habitat adjacent to the highway. Note that wildlife guards would have to be installed on both sides of each animal detection system to reduce the probability that Key deer will wander into the fenced road corridor.

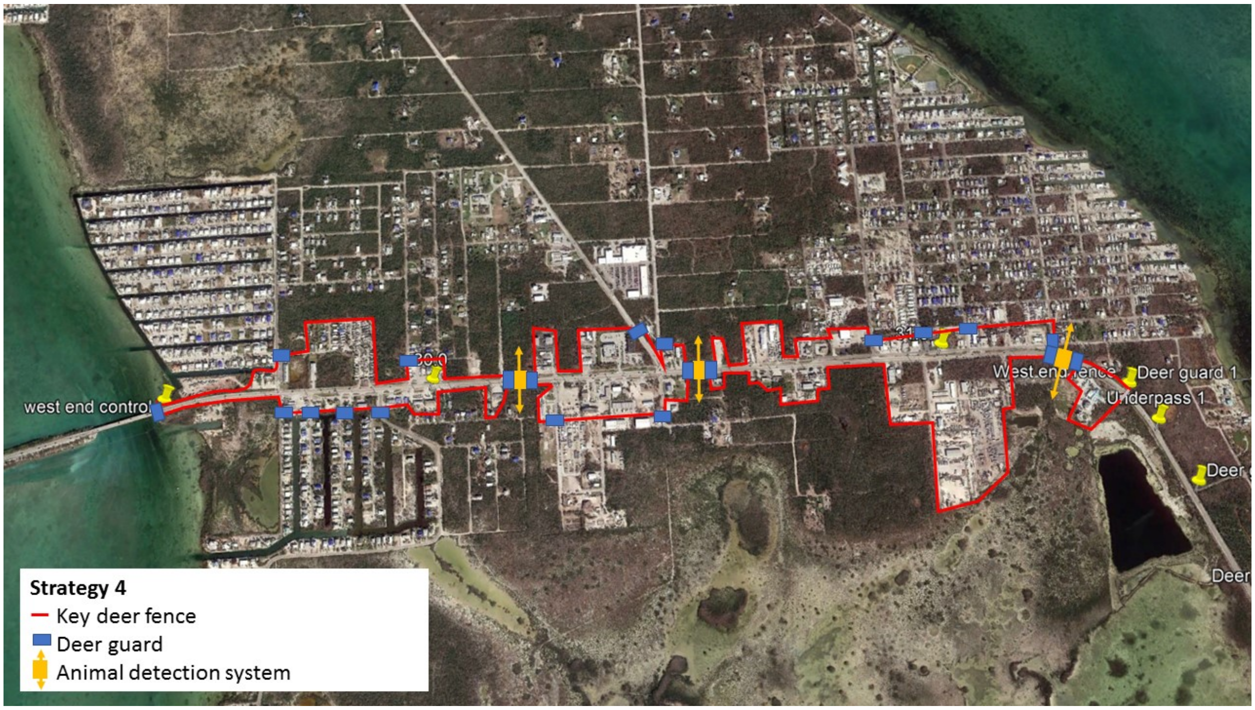

Figure 38: Example of potential future mitigation measures associated with strategy 4.

Pros	**Cons**
Assuming the effectiveness of the mitigation measures along the western section of US Hwy 1 will be similar to that of the animal detection systems elsewhere, with or without wildlife fencing, we can expect **between 33-97% reduction in Key deer-vehicle collisions along the western section of US Hwy 1 (Huijser et al., 2015a).** This would reduce the number of Key deer road mortalities and associated impacts to human safety in the western section of US Hwy 1 from 54.1 (SD = 18.7) to 1.6-41.7 per year (12.4-52.5 fewer Key deer road mortalities per year).	Note that the effectiveness of animal detection systems in reducing large mammal-vehicle collisions is very variable (33-97% reduction) and that many animal detection system projects fail for both technical and management reasons. Therefore, **the true effectiveness of animal detections systems in reducing Key deer-vehicle collisions is highly uncertain, and there may be safety and liability issues associated with encouraging Key deer to cross the highway, especially with relatively high traffic volume.**
Reduced human-wildlife conflict and improved wildness of key deer (reduced access to unnatural foods (non-native species in yards, hand-outs) through the exclusion of	**Reduction of road mortality may lead to faster population growth and further increase in population size of Key deer above the carrying capacity of the habitat**

the area immediately adjacent to the highway (Peterson et al., 2005).	and issues associated with overpopulation (e.g. starvation, disease).
Compared to strategy 2, access to businesses and residences along US Hwy 1 remains (largely) unhindered.	The area in between the fences is no longer accessible to Key deer. **The reduction in accessible habitat for the Key deer reduces the carrying capacity for Key deer and can result in a smaller population size.**
Compared to strategy 2, the visual impact of the wildlife fence and the wildlife fence hindering the view of businesses along US Hwy 1 is much reduced as the fence is largely behind the buildings that are adjacent to the highway.	**Acquiring or designating land that leads up to the safe crossing opportunities (here animal detection systems) may be difficult** from both an economic and social perspective. However, it is possible, including on private land (see e.g. the Key deer habitat conservation plan including the Sands Corridor for the area north of US Hwy 1 opposite of St. Peter Church near the western or northern fence end (Monroe County et al., 2006).
Compared to strategy 2 and 3, because of the safe crossing opportunities, the western section of US Hwy 1 would no longer be an absolute barrier to Key deer.	

6.7. Strategy 5: Combining Wildlife Fences (Strategy 3) with Safe Crossing Opportunities for Key Deer: Wildlife Underpasses or Overpasses

This strategy combines Strategy 3 with wildlife crossing structures (underpasses or overpasses) designed to allow Key deer and other wildlife species to safely cross US Hwy 1 (Figure 39). Underpasses and overpasses physically separate traffic and wildlife, and the use of wildlife crossing structures by ungulates is independent of the traffic volume (Dodd et al., 2007). Wildlife use of crossing structures has been widely documented (e.g. Clevenger & Waltho, 2000; Andis et al., 2017), and use of underpasses by Key deer has also been recorded (Braden et al., 2008; Parker et al., 2011). The examples of the locations for wildlife crossing structures (Figure 39) are indicative and based on a combination of current hotspots of collisions with Key deer, remaining (semi) natural habitat adjacent to the highway, and topography (i.e. the approach for the bridge on the western edge of Big Pine Key).

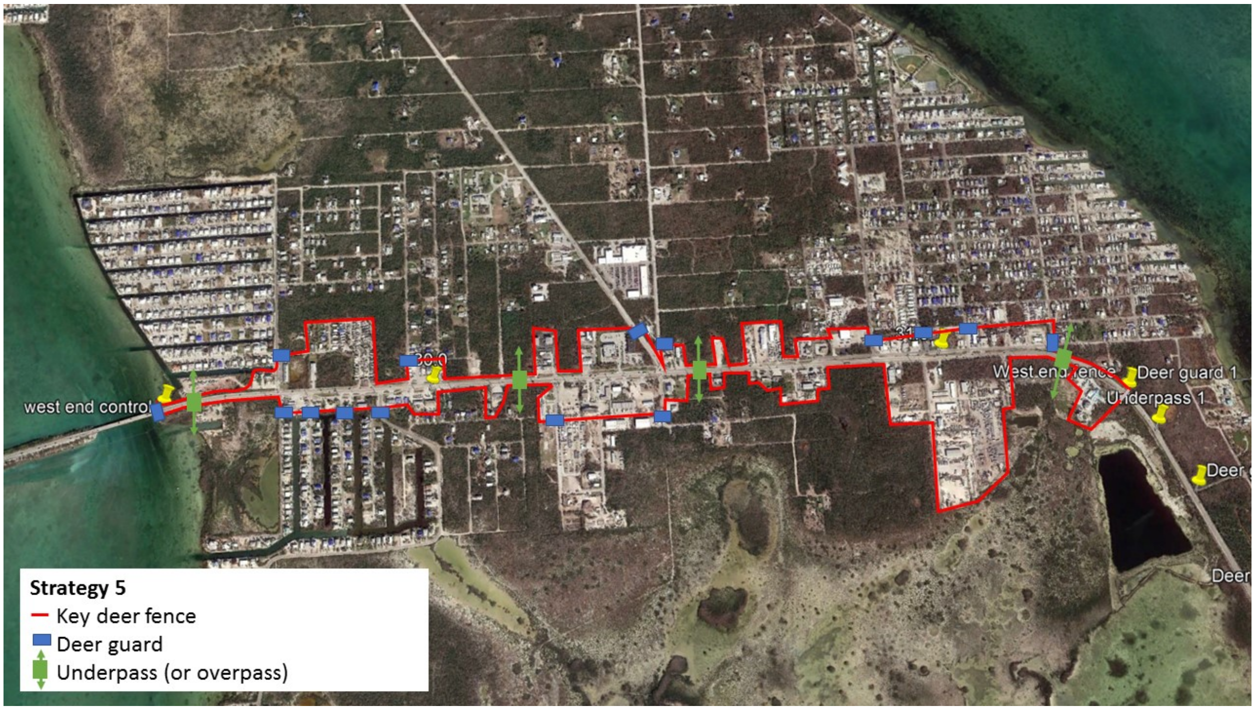

Figure 39: Example of potential future mitigation measures associated with strategy 5.

Pros	Cons
Assuming the effectiveness of the mitigation measures along the western section of US Hwy 1 will be similar to that of the mitigation measures along the eastern section of US Hwy 1, we can expect **93.9% reduction in Key deer-vehicle collisions along the western section of US Hwy 1.** This would reduce the number of Key deer road mortalities and associated impacts to human safety in the western section of US Hwy 1 from 54.1 (SD = 18.7) to 3.3 per year (50.1 fewer Key deer road mortalities per year). Through fencing the western portion of US Hwy 1, the **total number of Key deer-vehicle collisions would be reduced by 50.1 from 90-160 per year to 40-110 per year**.	**Reduction of road mortality may lead to faster population growth and further increase in population size of Key deer above the carrying capacity of the habitat** and issues associated with overpopulation (e.g. starvation, disease).
Reduced human-wildlife conflict and improved wildness of key deer (reduced access to unnatural foods (non-native species in yards, hand-outs) through the exclusion of the area immediately adjacent to the highway (Peterson et al., 2005).	The area in between the fences is no longer accessible to Key deer. **The reduction in accessible habitat for the Key deer reduces the carrying capacity for Key deer and can result in a smaller population size.**

Compared to strategy 2, access to businesses and residences along US Hwy 1 remains (largely) unhindered.	**Acquiring or designating land that leads up to the safe crossing opportunities (here animal detection systems) may be difficult** from both an economic and social perspective. However, it is possible, including on private land (see e.g. the Key deer habitat conservation plan including the Sands Corridor for the area north of US Hwy 1 opposite of St. Peter Church near the western or northern fence end (Monroe County et al., 2006).
Compared to strategy 2, the visual impact of the wildlife fence and the wildlife fence hindering the view of businesses along US Hwy 1 is much reduced as the fence is largely behind the buildings that are adjacent to the highway.	Constructing underpasses for Key deer would require **building up the roadbed of US Hwy 1 on both sides of the underpass locations**. Based on the existing underpasses under the eastern section of US Hwy 1, the roadbed may need to be built up about 200 m (219 yards) from either side of an underpass (total length elevated roadbed for one underpass would be 412 m (2*200 + width underpass 12 m (40 ft). Alternatively, wildlife overpasses would not affect the roadbed, but they would have approach ramps for wildlife extending perpendicular to the highway.
Compared to strategy 2 and 3, because of the safe crossing opportunities, the western section of US Hwy 1 would no longer be an absolute barrier to Key deer.	The road sections with a **built-up road bed** (about 200 m in either direction of an underpass) would have **no or reduced access for businesses or residences**. This may be (partially) addressed through frontage roads at the safe side of the fence. Alternatively, wildlife overpasses would not affect the roadbed and access to businesses and residences, but they would have approach ramps for wildlife extending perpendicular to the highway.

6.8. Strategy 6: Bypass for Big Pine Key

This strategy involves a long bridge to direct (most) through traffic around Big Pine Key and several islands further to the west (Figure 40). It has the potential to substantially reduce traffic volume on the highways on the islands where most of the Key deer habitat is.

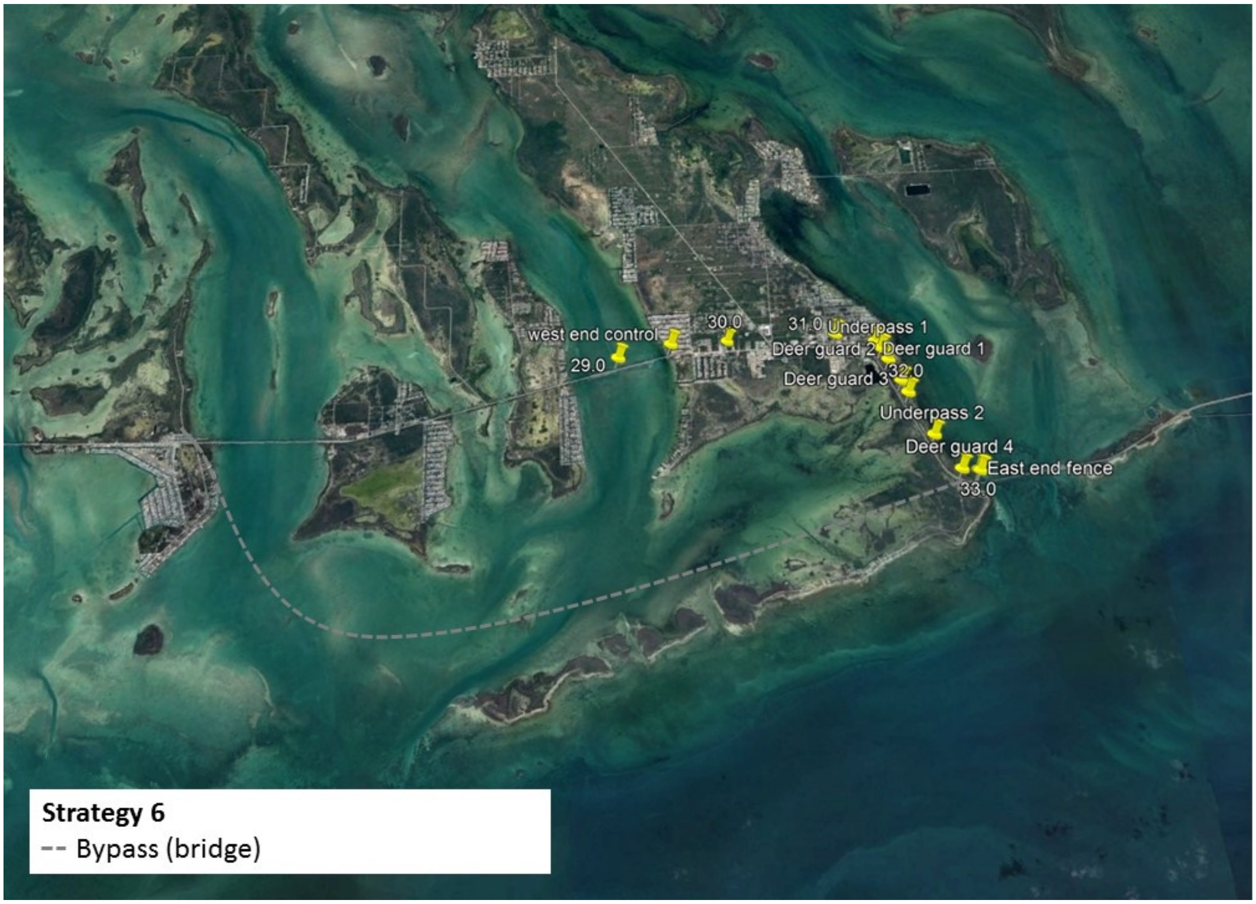

Figure 40: Example of potential future bypass.

Pros	Cons
A **substantial reduction in traffic volume on US Hwy 1 on Big Pine Key** is likely to result in a **substantial reduction in Key deer-vehicle collisions**. The extent of the possible reduction is not known, but it partially depends on how much traffic uses the bypass rather than the highway that bisects the islands.	**It is uncertain by how much Key deer mortality will be reduced** as US Hwy 1 on Big Pine Key will continue to have traffic.
Compared to strategy 2, access to businesses and residences along US Hwy 1 remains (largely) unhindered.	**Substantial reduction of road mortality may lead to faster population growth and further increase in population size of Key deer above the carrying capacity of the habitat** and issues associated with overpopulation (e.g. starvation, disease).
Compared to strategy 2, the visual impact of the wildlife fence and the wildlife fence hindering the view of businesses along US	**The construction of a long bypass is a very substantial and relatively expensive effort with its own set of environmental impacts.**

Hwy 1 is much reduced as the fence is largely behind the buildings that are adjacent to the highway.	
A bypass could potentially allow for a **higher posted speed limits and better traffic flow on US Hwy 1**, also during hurricane evacuation.	For example, a long bypass has strong **visual impacts** and potential **risks for sea birds colliding with vehicles**.
	A bypass is likely to result in **fewer "passer-by" clients for businesses** on the islands that are bypassed.

6.9. Strategy 7: Rebuild the Railroad, No Access for Vehicles from Mainland

This strategy would make the Florida Keys accessible by railroad and would stop access to cars from the mainland. Residents could still drive their vehicles on the islands, but travel between islands would likely be with the train. The railroad could potentially be built on the existing bridges that connect the islands (Figure 41). Shared use (electric) vehicles could potentially be made available on each of the islands to allow tourists to explore the individual islands. This strategy would take away most vehicle traffic and would most likely result in a substantial reduction in Key deer-vehicle collisions. It would potentially also reduce the space required for vehicles to drive and park on the islands. Space is at a premium, both for biological conservation and economic opportunities, especially when sea levels rise (e.g. Maschinsk et al., 2011; Zhang et al., 2011; Reece et al., 2013).

Figure 41: Example of potential future railroad, no access for vehicles from mainland.

Pros	Cons
Eliminating vehicles from the mainland and only allowing vehicles from residents will **substantially reduce Key deer-vehicle collisions.**	**Reduction of road mortality may lead to faster population growth of Key deer** and issues associated with overpopulation (e.g. starvation, disease).
Space is a premium on the islands, both for biological conservation and economic development. D**rastically reducing the space required to drive and park vehicles** opens possibilities for **habitat restoration** (e.g. for Key deer or other species) or for **economic development** that requires buildings or other objects (e.g. parking space for **shared use (electric) vehicles.**	**Spatial rearrangement of businesses around train stations and/or routes for shared use (electric) vehicles.**
It will be **easier for residents to travel on their individual islands** because through traffic by non-residents will be on the railroad.	**The construction of a railroad is a very substantial and relatively expensive effort.** However, the existing bridges may be used for the railroad as there would be no more

	access for vehicles from the mainland and no (or very limited) vehicle traffic between islands by residents.
A railroad could potentially result in a situation that allows for **more efficient transportation (no traffic jams),** also during **hurricane evacuation**.	

7. MORTALITY REDUCTION OPPORTUNITIES ALONG SECONDARY ROADS ON BIG PINE KEY

7.1. Introduction

This chapter explores potential future opportunities to reduce Key deer vehicle collisions on secondary roads on Big Pine Key and No Name Key (i.e. not US Hwy 1). These secondary roads include Key Deer Blvd, Wilder Rd-South St.- Ave. B-State Rte 4a, and Watson Blvd on Big Pine Key and No Name Key (Chapter 1, Figure 2).

7.2. Existing Measures

Existing measures aimed at reducing Key deer-vehicle collisions on the roads described above include low maximum posted speed limits (25 or 30 MPH), speed bumps, and a variety of warning and informational signs (Chapter 1, Figures 12-14). In addition, feeding of Key deer is illegal as unnatural food may be a threat to the health of the Key deer, can help spread diseases, disrupts their natural interaction with the environment (affects ecological integrity), and encourages them to spend more time on and along roads where they are exposed to vehicles. However, despite substantial enforcement, feeding of Key deer is common (Figure 42).

Figure 42: People feeding Key deer (this is not legal), No Name Key, Florida, USA.

7.3. Warning Signs

Most studies indicate that standard and enhanced wildlife warning signs do not reduce wildlife vehicle collisions (review in Huijser et al., 2015a). Wildlife warning signs that are specific in time and place can result in some reduction (temporary wildlife warning signs for migratory species) or a more substantial reduction (animal detection systems) in wildlife-vehicle collisions. If the objective is to reduce wildlife-vehicle collisions, then standard or enhanced wildlife warning signs are not an appropriate measure. However, if the objective is to provide legal protection to transportation organizations in case of a collision, to provide information to the public and increase awareness of the problem, and to potentially increase public support for other mitigation measures that are effective in reducing wildlife-vehicle collisions, then one may consider using standard or enhanced wildlife warning signs.

7.4. Speed Management

Drivers typically drive a speed that reflects the design speed rather than the maximum posted speed limit. Therefore, substantially lowering the maximum posted speed limit below the design speed is not an effective strategy (Huijser & Ferraz, 2015). However, speed bumps have been implemented on select locations along some of the secondary roads on Big Pine Key. This is a measure that affects the design speed and is more likely to result in lower operating speeds.

If drivers encounter a very large animals (i.e. a moose) on the highway in the dark, and if they drive with low beams to not blind the drivers coming from the opposite direction, about half of the drivers will not be able see the animal in time to allow for the avoidance of a collision if they drive 40 MPH (Huijser et al., 2017). Smaller animals (e.g. Key deer) are likely detected at much shorter distances than moose and more likely to be hit. Nonetheless, if vehicles have an operating speed of 25-30 MPH, consistent with the posted speed limit on the secondary roads on Big Pine Key, it is likely that many drivers will be able to avoid a collision with Key deer in the dark. It is advisable to keep the low posted speed limits and enforce the low posted speed limits.

7.5. Unnatural food for Key deer

Feeding encourages Key deer to spend time along roads where they are then more likely to be hit by vehicles. While it is hard to accomplish, especially with many non-residents cruising the roads to view deer, it seems worthwhile to increase efforts to change people's behavior and make it clear and culturally unacceptable to feed deer. There are already signs that state that feeding Key deer is illegal, and there already is substantial enforcement. Yet, feeding of Key deer is still common. Consider efforts that encourage members of the public, especially residents, to educate people feeding Key deer. Feeding deer is bad for their health and it can lead to their death, including through collisions with vehicles as it draws the deer to roads and are habituated to people.

A greater effort at informing visitors that feeding Key deer is illegal and not acceptable can perhaps be initiated from the proposed new nature center along US Hwy 1 (KBP Consulting, Inc. 2017). However, not all visitors will stop there. Therefore, consider having a “entrance station” at Key deer Blvd and making lanes for residents (pass without delay) and lanes for visitors (receive mandatory instructions to not speed, do not feed the Key deer, do not litter, especially not food items).

Also consider the use of garbage cans that are harder to access by Key deer and other wildlife. The current “corals” around garbage bins are often broken or ineffective, and many garbage cans have lids that are easily opened by animals (Figure 43). As a result, Key deer and other wildlife species can easily access food in the garbage cans that are placed along the roads.

Figure 43: Garbage cans and coral to keep the cans from being toppled by Key deer, Big Pine Key, Florida, USA.

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