Impacts of Roads and Traffic on the Red Wolf: Potential Avoidance, Mitigation and Compensation Strategies

by

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FINAL REPORT

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A report prepared for the
U.S. Fish & Wildlife Service, Headquarters Office,
Transportation & Data Management Branch, 5275 Leesburg Pike, Falls Church, VA 22041

September, 2023

DISCLAIMER

ACKNOWLEDGEMENTS

The authors of this report would like to thank the U.S. Fish & Wildlife Service (USFWS) for funding this project.

Special thanks are due to Joe Madison and Art Beyer, Red Wolf Recovery Program, U.S. Fish and Wildlife Service (USFWS). Additional thanks are due to:

- Dennis Stewart, retired
- Ron Sutherland, Wildlands Network
- Paul Williams, North Carolina Department of Transportation
- Travis Wilson, North Carolina Wildlife Resources Commission
- Vince Ziols (USFWS)

TECHNICAL DOCUMENTATION

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4W9830	N/A	N/A

4. Title and Subtitle Impacts of roads and traffic on the red wolf: Potential avoidance, mitigation and compensation strategies	**5. Report Date** September 2023 **6. Performing Organization Code**
7. Author(s) Marcel P. Huijser & James S. Begley	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Western Transportation Institute P.O. Box 174250 Montana State University Bozeman, MT 59717-4250	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 4W9830
12. Sponsoring Agency Name and Address U.S. Fish & Wildlife Service, Headquarters Office, Transportation & Data Management Branch, 5275 Leesburg Pike, Falls Church, VA 22041	**13. Type of Report and Period Covered** Research report 1 October 2022 – 22 September 2023 **14. Sponsoring Agency Code**

15. Supplementary Notes
A PDF version of this report is available from WTI's website at www.westerntransportationinstitute.org

16. Abstract

The red wolf (*Canis rufus*) is listed as endangered under the Endangered Species Act. In 1980, the species was declared extinct in the wild, but the species survived in captivity. A mainland reintroduction effort to establish an eastern North Carolina red wolf population (ENC RWP) was initiated in Alligator River National Wildlife Refuge (ARNWR) in North Carolina in 1987. The population grew and remained relatively stable between 2001 and 2014 (81-110 individuals), but severely declined afterwards. While the population size was very low between 2019 and 2022, it had stabilized around 18-20 individuals and increased to an estimated 32-34 individuals in June 2023. Of all reported mortalities, vehicle strikes (19.96%) were one of the most frequently occurring known causes of death. This report summarizes the number of direct road mortalities, their location, and mitigation measures aimed at reducing direct road mortality while maintaining habitat connectivity across roads.

17. Key Words barrier, Canis rufus, collisions, connectivity, conservation, corridors, crashes, crossing structures, culverts, fences, habitat, highway, hotspot, mitigation measures, plan, prioritization, procedures, ranking, recovery, red wolf, strategy, strategies, tools, traffic volume, tunnels, underpasses, wildlife, wildlife–vehicle collisions, wolf	**18. Distribution Statement** Unrestricted. This document is available through U.S. Fish & Wildlife Service and WTI-MSU.

19. Security Classification (of this report)	20. Security Classification. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	118	

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SUMMARY

The red wolf (*Canis rufus*) is listed as endangered under the Endangered Species Act. In 1980, the species was declared extinct in the wild, but the species survived in captivity. After successful captive breeding efforts, trial releases were initiated, including on several islands. A mainland reintroduction effort to establish an Eastern North Carolina Red Wolf Population (ENC RWP) was initiated in Alligator River National Wildlife Refuge (ARNWR) in North Carolina in 1987. The red wolves in this area are categorized as a nonessential experimental population (NEP). The NEP area includes federal, state, and private lands in Beaufort, Dare, Hyde, Tyrrell, and Washington Counties, on the Albemarle Peninsula of North Carolina.

In general, the red wolf population size in the NEP area increased between 1987 and 2000, remained relatively stable between 2001 and 2014 (81-110 individuals), and severely declined afterwards. While the population size was very low between 2019 and 2022, it stabilized around 18-20 individuals, increasing to an estimated 32-34 individuals in June 2023. Of all reported mortalities between 29 April 1987 and 27 June 2022 (N=471), gunshot (N=122, 25.90%) and vehicle strike (N=91, 19.96%) were the most frequently occurring known causes of death. Both causes of mortality, gunshots and vehicle strikes, are unnatural and can be considered problematic for a threatened species, especially one that has a critically low population size and a high risk of extirpation in the ENC RWP. The average percentage of vehicle strikes per year out of the estimated population size was 5.38% (SD = 5.21). In other words, based on the historic data, each year about 5% of the red wolf population has died because of vehicle strikes.

While collisions with red wolves are widespread along the major highways as well as smaller roads throughout the ENC RWP area, including unpaved roads, there are 6 road sections that had a higher concentration of collisions than other road sections. System roads (paved roads maintained by NCDOT) had 78 recorded red wolf road mortalities with a known location. The traffic volume category 101-500 vehicles per day had more red wolf road mortalities (N=26, 33.33% of all reported road mortality on system roads) than the other traffic volume categories. Overall, the vast majority of all direct red wolf road mortalities (N= 72, 92.31%, of all reported road mortality on system roads) occurred on roads between 101 and 5,000 vehicles per day. This means that if the total road mortality of red wolves is to be substantially reduced in the ENC RWP area, the historic data suggest that the efforts should be focused on roads with a traffic volume between 101-5,000 vehicles per day. Efforts aimed at reducing road mortality of red wolves along busier roads in the ENC RWP area (>5,000 vehicles per day) would not be an effective strategy. Roads with 2,501-5,000 vehicles per day had a factor 2.34 more red wolf road mortalities than expected if traffic volume did not influence road mortality. This means that implementing mitigation measures along roads with a traffic volume of 2,501-5,000 vehicles per day would be most "efficient" with the highest number of red wolf road mortalities addressed for the shortest mitigated road length. Traffic volume categories with a traffic volume between 0-2,500 vehicles per day had red wolf road mortalities that were roughly proportional to their road length. The lowest ("unknown, but low") and highest traffic volume categories (>5,000 vehicles per day) had proportionally very few road mortalities of red wolves, and this is where mitigation measures would be most "inefficient" with the fewest red wolf road mortalities addressed for the road length mitigated.

Road sections with the highest numbers of birth locations close to the road can be considered the most dangerous to breeding red wolves and their offspring, regardless of whether direct red wolf mortality has occurred in the past. These potentially dangerous road sections are along roads with both relatively high and low traffic volumes. They include Frying Pan Rd, US Hwy 64 (Miltail Rd area), Beech Ridge Rd, US Hwy 264 (landfill area), SR 1305 (northwest of Lake Mattamuskeet), SR 1304 (Turnpike Rd, west of Lake Mattamuskeet), SR 1105 (near Miles Liverman Cemetery, SE Columbia), and SR 1311, northeast of Lake Mattamuskeet.

Road mortality of red wolves does not only occur along US Hwy 64, the highway with the highest traffic volume in the area (about 4,000 vehicles per day). Therefore, a possible road reconstruction project of US Hwy 64 and associated mitigation measures for the red wolf would only address a portion of the red wolf road mortality problem (24.36%). If the main objective is to substantially reduce road mortality of red wolves, a more integral approach is needed for all highways in the ENC RWP area. In addition to US Hwy 64, measures are likely most needed along US Hwy 264 and Hwy 94. Since these highways have much lower traffic volume (ranging from a few hundred vehicles per day up to about 1,000 or 2,000 vehicles per day), general road reconstruction for these highways is unlikely to be initiated because of human safety or traffic congestion concerns. Stand-alone mitigation measures would have to be initiated for the red wolf to substantially reduce the overall direct road mortality in the population.

While it is considered bad practice to only implement wildlife fences and not combine them with safe crossing opportunities for wildlife, immediate wildlife fencing along US Hwy 64 and parts of US Hwy 264 may be what is needed for the immediate survival of the few remaining red wolves (situation in 2022-2023). However, if wildlife crossing structures are not an integral part of the mitigation measures, other species may suffer, and for the long-term conservation of the red wolf, habitat connectivity is also essential. Habitat connectivity is especially important along US Hwy 94, and select sections of US Hwy 264, as there are large areas with suitable habitat and historic evidence of birth locations on both sides of the highways. Furthermore, if wildlife crossing structures are not implemented at the same time as wildlife fences, the wildlife crossing structures may never be implemented, despite the good intentions.

A fence designed to keep red wolves off the highway should probably have the following characteristics: 10 ft high, metal fence posts, chain-link fence material, dig barrier or apron, overhang, potentially electrified wires attached to the main fence on the safe side of the fence, high-tensile wire on top, but adjust or reconsider location in combination with an overhang. Crossing structures that suitable for red wolves should probably be wildlife overpasses (50-70 m wide) or large underpasses (at least about 30 m wide and 3-4 m high), have gradual approaches (slope), be combined with bridges over canals that may be adjacent to the highway, and no human access to the structures.

The mitigation measures (primarily wildlife fences in combination with wildlife crossing structures), should be implemented over long road sections (i.e., at least 5-7 miles of road length, and likely much longer). Shorter road sections are less likely to be effective in reducing the mortality in the mitigated road section, and it may move the road mortality to the adjacent road sections rather than reduce the overall road mortality.

Wildlife fences, wildlife crossing structures and associated measures may be considered costly, especially if they are initiated as a stand-alone project rather than as part of a general road reconstruction project. However, there are also costs to doing nothing. Historically we have mostly paid attention to vehicle repair costs and the costs associated with human injuries and human fatalities when we hit large wild mammals. It is relatively new to also pay attention to economic parameters associated with wildlife conservation. For large mammals that are endangered and considered charismatic by the public, an individual animal may be valued at several tens of thousands up to several million dollars. In this context, it may not be "cost prohibitive" to implement mitigation measures for red wolves. Even stand-alone mitigation projects for species similar to the red wolf may be considered defensible on economic arguments alone.

1. INTRODUCTION

1.1. Background

The red wolf (*Canis rufus*) is listed as endangered under the Endangered Species Act (USFWS 2021). While there has been some uncertainty in the past, there is now consensus that the red wolf is a distinct species (National Academies of Sciences, Engineering, and Medicine 2019). Before settlement by Europeans, the red wolf was common throughout the eastern and south-central United States. However, intentional killing and habitat loss caused a severe population decline. By 1972, the red wolf only remained present in a coastal area near the Texas-Louisiana border (USFWS 2018). The remaining red wolves were captured and screened for hybridization with coyotes (*Canis latrans*). Of the captured canids, only 43 individuals met the criteria for a red wolf captive breeding program. Of these animals, only 14 animals eventually became the founding stock and only 12 of them still have living descendants (USFWS 2018). In 1980, the species was declared extinct in the wild.

After successful captive breeding efforts, trial releases were initiated on Bulls Island in Cape Romain National Wildlife Refuge in South Carolina. Here, the first red wolves were released in 1978, and they were present until 2005 (USFWS 2022a). In 1990, the U.S Fish and Wildlife Service (USFWS) established an island propagation site for the red wolf at St. Vincent National Wildlife Refuge, an isolated island off the Gulf Coast of Florida. The role of this site is to maintain a breeding pair of red wolves in the wild in a somewhat controlled, but natural environment (e.g., no paved roads, no residents, very limited hunting) that will provide their pups with wild experience as juveniles for the purpose of being captured and strategically translocated to North Carolina at the age of dispersal (USFWS 2021). A mainland reintroduction effort to establish an Eastern North Carolina Red Wolf Population (ENC RWP) was initiated in Alligator River National Wildlife Refuge (ARNWR) in North Carolina in 1987 (USFWS 2018). The red wolves in this area are categorized as a nonessential experimental population (NEP). The NEP area includes federal, state, and private lands in Beaufort, Dare, Hyde, Tyrrell, and Washington Counties, on the Albemarle Peninsula of North Carolina (USFWS 2018). Over 60 adults were released between 1987-1994 and by the mid-1990s wild red wolves had established territories, operated in packs, and reared young successfully. Breeding pairs reared their natural born young, as well as foster pups that were born in captivity and placed in the den by USFWS personnel. Red wolf packs almost exclusively consist of a breeding pair and their natural born young of that year (or foster pups), and those from prior years. Red wolves do not typically adopt individuals as pack members if they were born to another pack (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). Once a breeding male or female dies, this results in a disruption of reproduction, and a replacement mate may not be readily available at low population density (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program).

In 2012 the wild red wolf population size peaked and was estimated at about 120 individuals (USFWS 2021). After 2012 a decline set in, with only 15-17 estimated in the wild in October 2021 (USFWS 2021). Eight of these individuals wore a collar. Most important causes for the decline over the last decade are anthropogenic mortality, mostly gunshots and collisions with vehicles (USFWS 2018). Other threats include hybridization with coyotes, and stochastic events due to small population size (USFWS 2018). The captive population of red wolves was 241 individuals in October 2021 (USFWS 2021).

Release efforts were reinitiated in February 2020 with the translocation and release of one red wolf from St. Vincent National Wildlife Refuge to the ENC RWP, then another two in February 2021. In spring 2021, four captive born adult red wolves (two pairs) were released into the ENC RWP and four captive born pups were fostered into a wild red wolf den (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). Additional releases occurred in the winter/spring of 2021-2022 with the release of ten red wolves into the ENC RWP (three pairs (six adults, one of the pairs had three young, and one adult was paired with a captured wild red wolf)) (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). In spring 2023, seven red wolves were released into the ENC RWP, including six captive born red wolves and one red wolf translocated from St. Vincent National Wildlife Refuge. These red wolves were part of creating three pairs of which one was a wild red wolf, and one was captive born, as well as captive born family group consisting of a pair and a yearling at the time of release. One of the newly formed pairs and the family group both had pups prior to release, which added seven pups to the population. Additionally, a captive born pup was fostered into a wild red wolf den in April 2023. The red wolf population was estimated at 32-34 individuals in June 2023 (USFWS 2023). In recent years vehicle mortality has continued to be an issue. The following mortalities are suspected to be caused by vehicles: 8 May 2022, breeding female (2133F), 7 October 2022, female pup from the litter born at ARNWR in April 2022 (USFWS 2023). Since direct road mortality is one of the main causes of unnatural deaths for red wolves, particularly for captive born red wolves that have been released into the wild, there is great interest in exploring measures that reduce direct road mortality (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program).

1.2. Goals, objectives and tasks

The goal of this report is to contribute to having a more viable population of wild red wolves within the ENC RWP area (i.e., the Beaufort, Dare, Hyde, Tyrrell, and Washington Counties, North Carolina).

The objectives of this project are to:

1. Provide advice on measures that are likely to substantially reduce direct road mortality for red wolves in the ENC RWP area.
2. Provide advice on measures that are likely to provide safe crossing opportunities for red wolves in the ENC RWP area.

The tasks for this project include:

A. Data collection tasks:

1. Obtain wild red wolf mortality data (all causes) for the ENC RWP, for all years.
2. Obtain historic and current approximate territories, home ranges, or use areas of breeding packs.

3. Obtain historic data of potential use of underpasses (including culverts) by red wolves in the ENC RWP area, or perhaps a broader area, including the crossing structures further west along US Hwy 64.
4. Historic road crossing locations based on road-killed individuals (see road mortality data above), visual observations of successful crossings, or road crossing locations based on radio or GPS collar data.
5. Obtain data on existing culverts/underpasses (for wildlife, for hydrology, for vehicles, pedestrians etc.) in the ENC RWP area.

B. Background, analyses, and syntheses tasks:

6. Conduct a literature review and survey of expert opinion on the suitability of wildlife fences (height, fence material, posts, overhang, dig barrier), type of crossings structure (underpasses, overpasses) and the dimensions of crossing structures for red wolf or closely related species (e.g., gray wolf, coyote) (e.g., Smith 2011).
7. Select highway sections (all paved roads) that are within the territories, home ranges, or use areas or "near" these areas, and select the associated direct mortality data of red wolves along these road sections. These are the road sections that may need to be addressed first, as these are in high quality habitat where breeding adults are at greatest risk of direct vehicle mortality. Other road sections may have red wolf road mortality of predominantly juvenile or dispersing red wolves, including in marginal or suboptimal habitat. Sections of US Hwy 64, State Highway 94, and US Hwy 264 are likely of particular interest. Compare these selections to those from other studies conducted in the area that aimed to identify road sections for potential mitigation measures for large mammals (e.g., Smith 2011, Vaughan et al. 2011a, Vaughan et al. 2011b).
8. Conduct a field review of the road sections and surrounding areas that rank highest based on their location in relation to historic or current territories or home ranges of breeding pairs of red wolves.
    a. Assess the options for potential mitigation measures along these road sections.
    b. Interview stakeholders (USFWS, NCDOT, NGOs, etc) with regard to their perspectives on direct road mortality of red wolves, the barrier effect that roads and traffic may represent to red wolves, and road mitigation measures for red wolves that would contribute most to the conservation of this species.
9. Produce a draft report, a PowerPoint presentation to USFWS (through zoom or other video link), and a final report.

2. EFFECTS OF ROADS AND TRAFFIC ON WILDLIFE

Roads and vehicles can affect wildlife in several ways. In general, not specific for the red wolf, there are five different categories of the effects of roads and traffic on wildlife (Figure 1) (e.g., van der Ree et al. 2015):

- Habitat loss: e.g., the paved road surface, heavily altered environment through the road-bed with non-native substrate, altered hydrology, vegetation removal, seeded species and mowing in the clear zone.
- Direct wildlife road mortality because of collisions with vehicles.
- Barrier to wildlife movements: e.g., animals do not cross the road as often as they cross natural terrain and only a portion of the crossing attempts is successful.
- Decrease in habitat quality in a zone adjacent to the road: e.g., noise and light disturbance, air and water pollution, increased access to the areas adjacent to the highways for humans and associated disturbance.
- Right-of-way habitat and corridor: Depending on the surrounding landscape, the right-of-way can promote the spread of non-native or invasive species (surrounding landscape largely natural or semi-natural) or it can be a refugium for native species (surrounding landscape heavily impacted by humans).

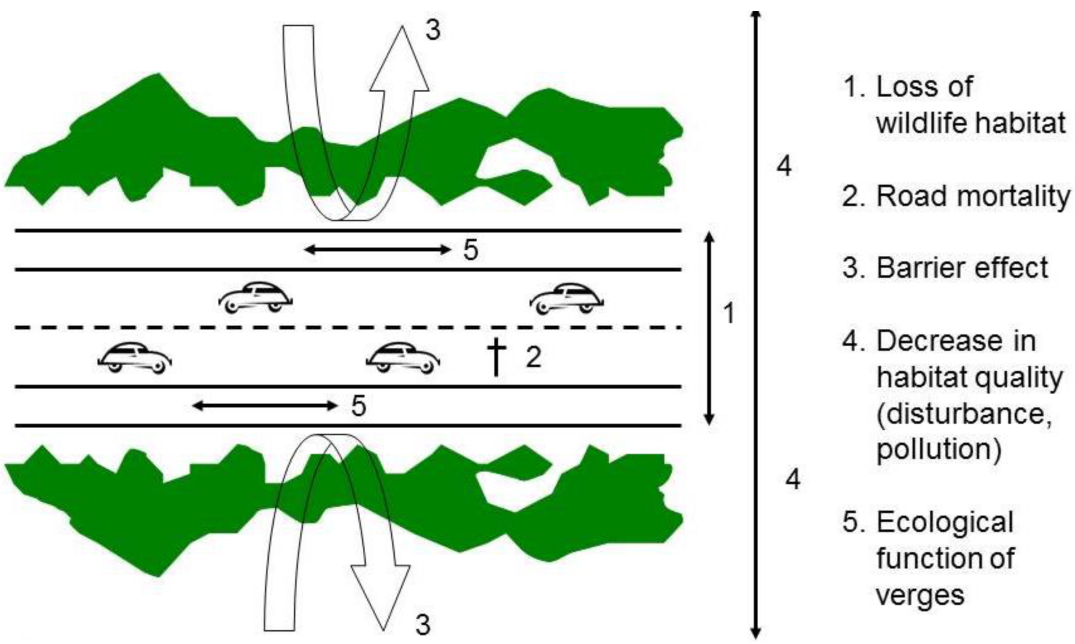

Figure 1: The effects of roads and traffic on wildlife.

While the effects of roads and traffic are varied, direct road mortality, either for the purpose of human safety or biological conservation, and the barrier effect are most commonly addressed. Habitat loss, a decrease in habitat quality in a zone adjacent to a road, and the spread of non-native invasive species are acknowledged and dealt with less often.

3. AVOIDANCE, MITIGATION, AND COMPENSATION STRATEGIES

While mitigation (reducing the severity of an impact) is common, avoidance is better and should generally be considered first (Cuperus et al. 1999). For example, the negative effects of roads and traffic may be avoided if a road is not constructed, or the most severe negative effects may be avoided by re-routing away from the most sensitive areas (Figure 2). If the effects cannot be avoided, mitigation is a logical second step. Mitigation is typically done in the road-effect zone (Figure 2) and may include measures aimed at reducing wildlife-vehicle collisions and reducing the barrier effect (e.g., through providing for safe wildlife crossing opportunities) (Clevenger & Huijser 2011, Huijser et al. 2021). However, mitigation may not always be possible, or the mitigation may not be sufficient. In such situations, a third approach may be considered: compensation or off-site mitigation. Compensation may include increasing the size existing habitat patches, creating new habitat patches, or improving the connectivity between the habitat patches that would allow for larger, more connected, and more viable network populations. Finally, in some situations, a combination of avoidance, mitigation, and compensation may be implemented.

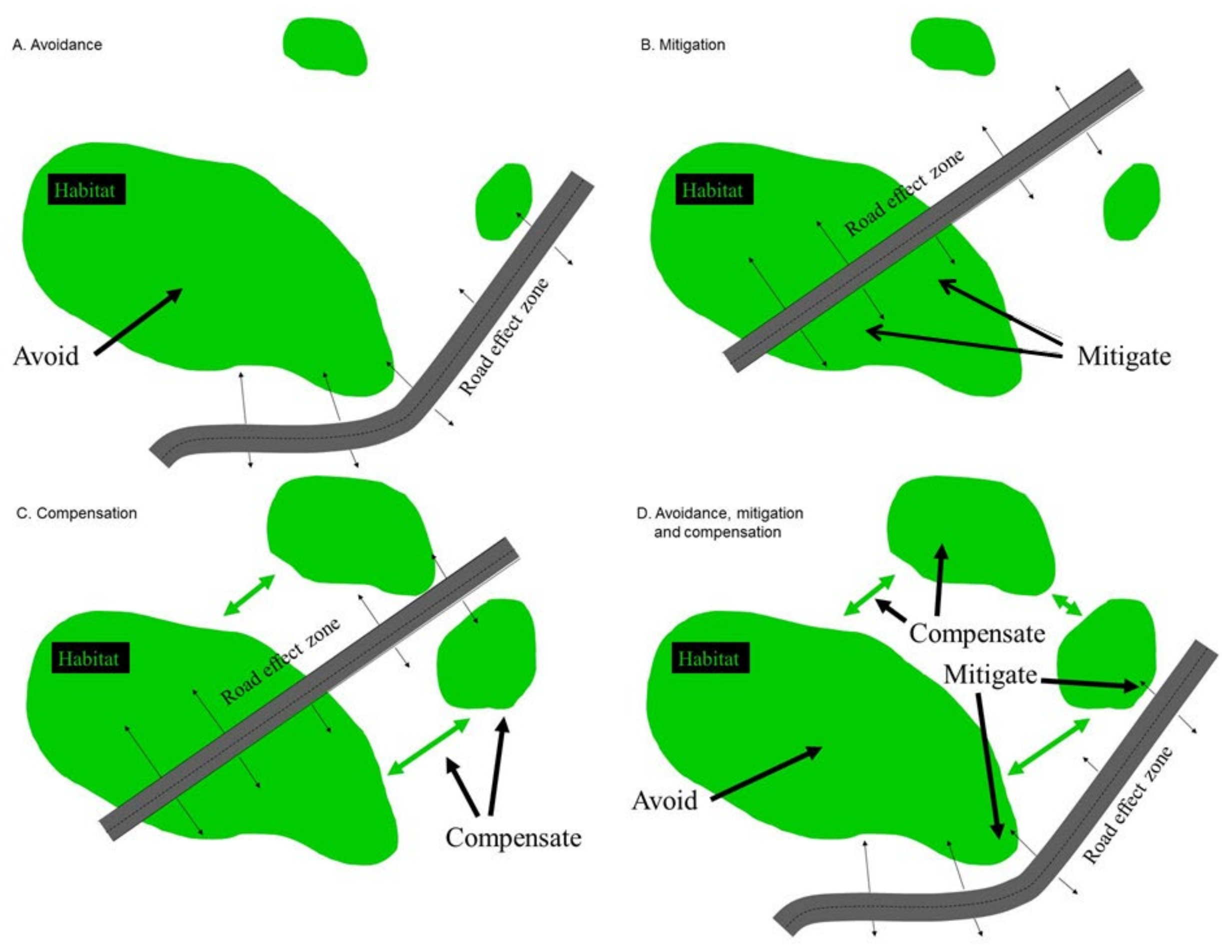

Figure 2: A three step approach: A. Avoidance, B. Mitigation, C. Compensation, D. Combination of avoidance, mitigation and compensation.

4. DIRECT ROAD MORTALITY OF WILD RED WOLVES

4.1. Road mortality numbers

Of all reported mortalities vehicle strikes (N=91, 19.96%) was one of the most frequently occurring known causes of death (Appendix). The frequency of this unnatural mortality can be considered problematic for a threatened species, especially one that has a critically low population size and a high risk of extirpation in the ENC RWP. There was no clear seasonal pattern for mortality because of vehicle strikes (Appendix). Absolute mortality because of vehicle strikes was positively correlated with increasing population size (Appendix). The average percentage of vehicle strikes per year out of the estimated population size was 5.38% (SD = 5.21) (Appendix).

4.2. Hotspot analysis

We investigated where the highest concentrations of red wolf roadkills were between 29 April 1987 and 27 June 2022 (91 reported roadkilled red wolves in total). To identify hotspots, we conducted a Kernel density analysis using ArcGIS 10.6.1 (ESRI 2018) for point features of red wolf-vehicle collision locations using a 25 m cell size (82 ft × 82 ft). A 25 m cell size is relatively fine scale but still accommodates for some spatial inaccuracies in GPS coordinates. The Kernel density analysis calculates the density of roadkills in a neighborhood around each cell and is based on the quartic kernel function described by Silverman (1986). We set the neighborhood search radius at 1,000 m (0.62 mi). On a straight road this means that red wolf roadkill that are up to about 1,000 m away are included in the density analysis for each cell. To help interpret the results of the Kernel density analyses and identify hotspots, we displayed the raster output using a heat map classification with varying densities of red wolf roadkills collisions. We used percentage breaks to create five categories (<5%, 5-<25%, 25-<50%, 50-<75%, and 75–100%) that display the areas with the highest densities of red wolf roadkills collisions (<5%) to areas with the lowest densities (75-100%).

While collisions with red wolves are widespread along the major highways as well as smaller roads throughout the ENC RWP area, there are 6 road sections that have a concentration of collisions in the two highest density categories (orange and red) (Figure 3, 4):

- Zoom 1 (Figure 5). US Hwy 64, through and adjacent to Alligator River National Wildlife Refuge.
    - Around Lake Neighborhood Rd./River Rd. – Buffalo City Rd.
    - Around Milltail Rd.
    - Just west of the junction with US Hwy 264.
- Zoom 2 (Figure 6). US Hwy 264, around Long Shoal River/Stomper Rd.
- Zoom 3 (Figure 7). US Hwy 264, north of Engelhard.
- Zoom 4 (Figure 8). Hwy 94, Columbia – Northwest Fork Alligator River.
- Zoom 5 (Figure 9). Hwy 94, north of Fairfield.
- Zoom 6 (Figure 10). Beech Ridge Rd., north of Belhaven.

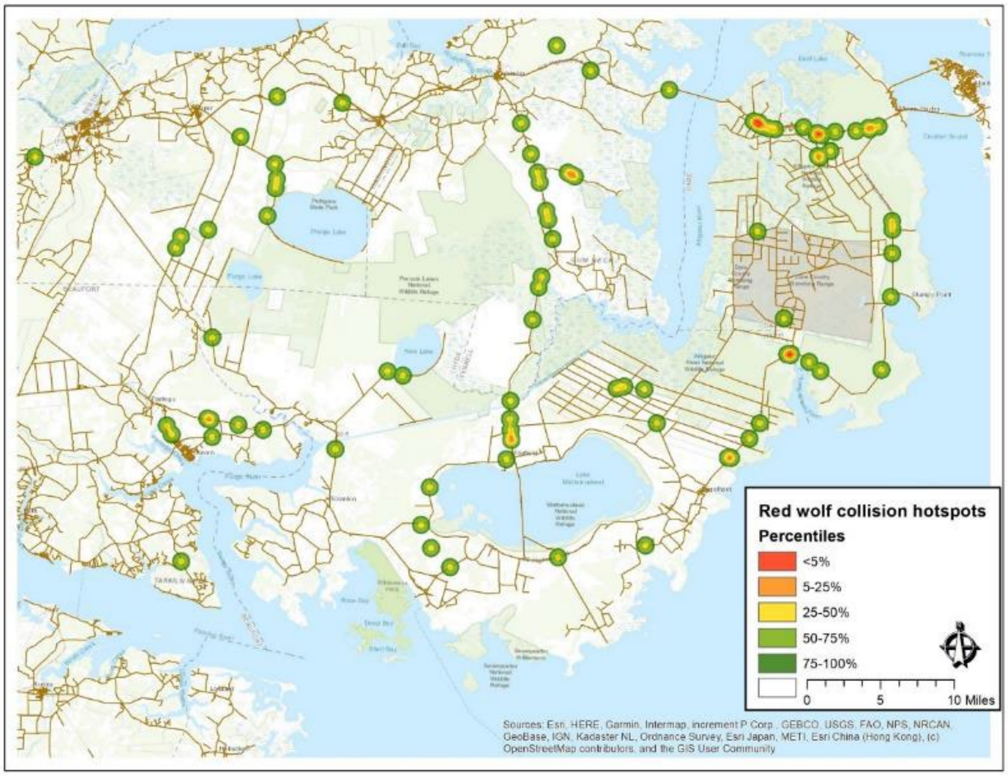

Figure 3: Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

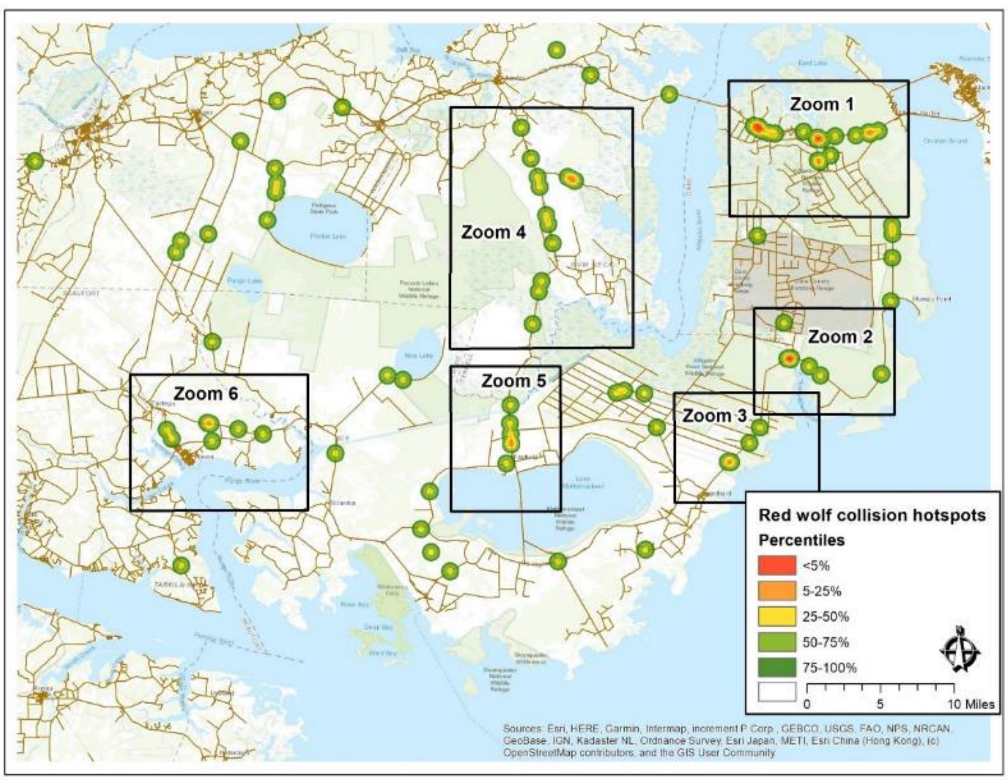

Figure 4: Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022), overview Zoom 1-6.

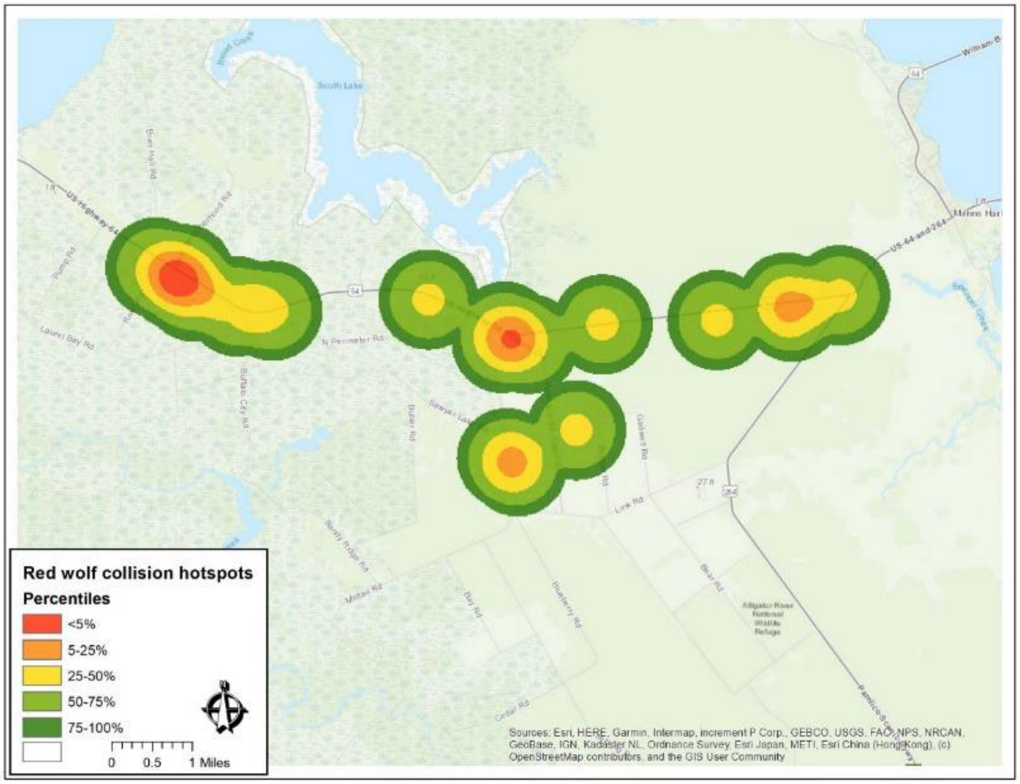

Figure 5: Zoom 1, US Hwy 64. Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

Figure 6: Zoom 2, US Hwy 264. Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

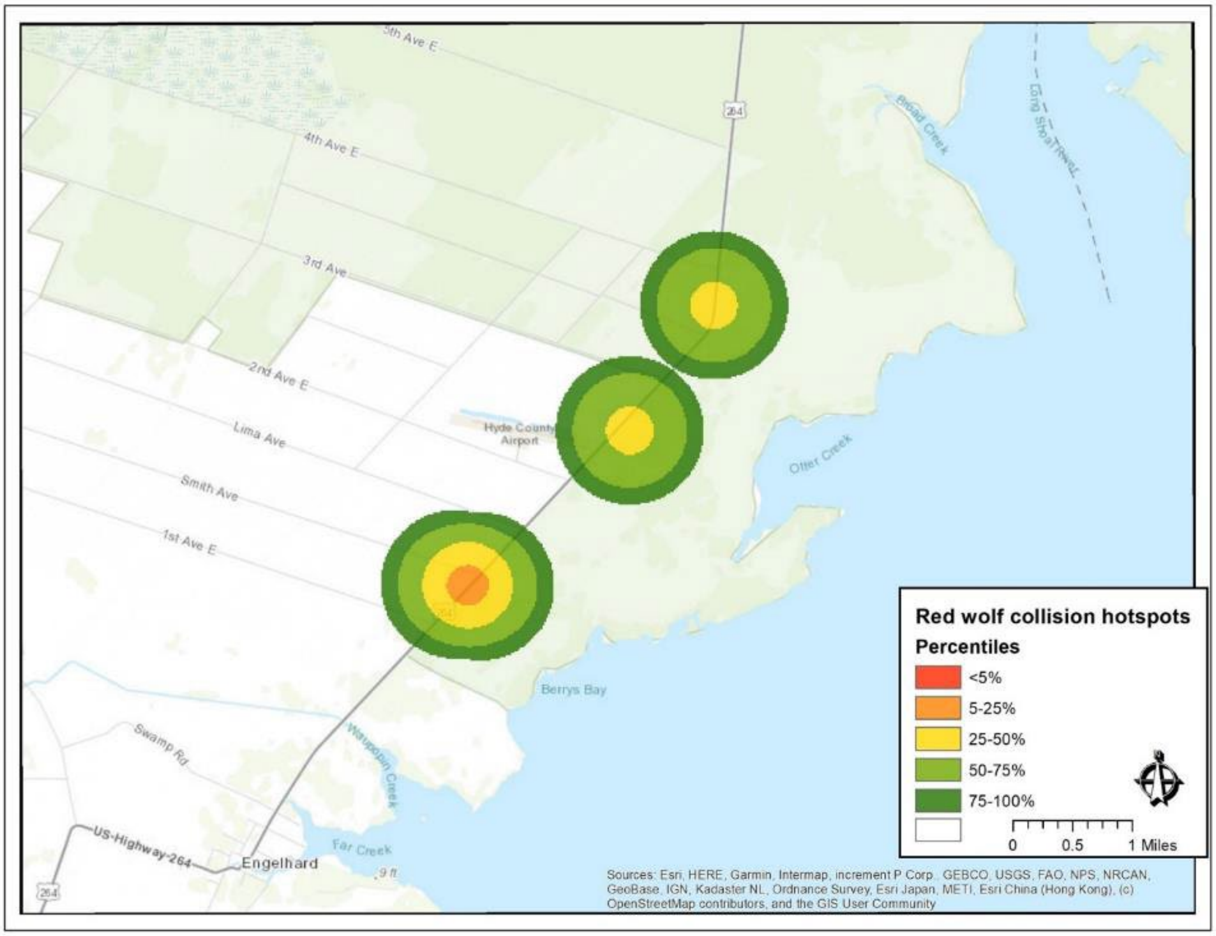

Figure 7: Zoom 3, US Hwy 264. Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

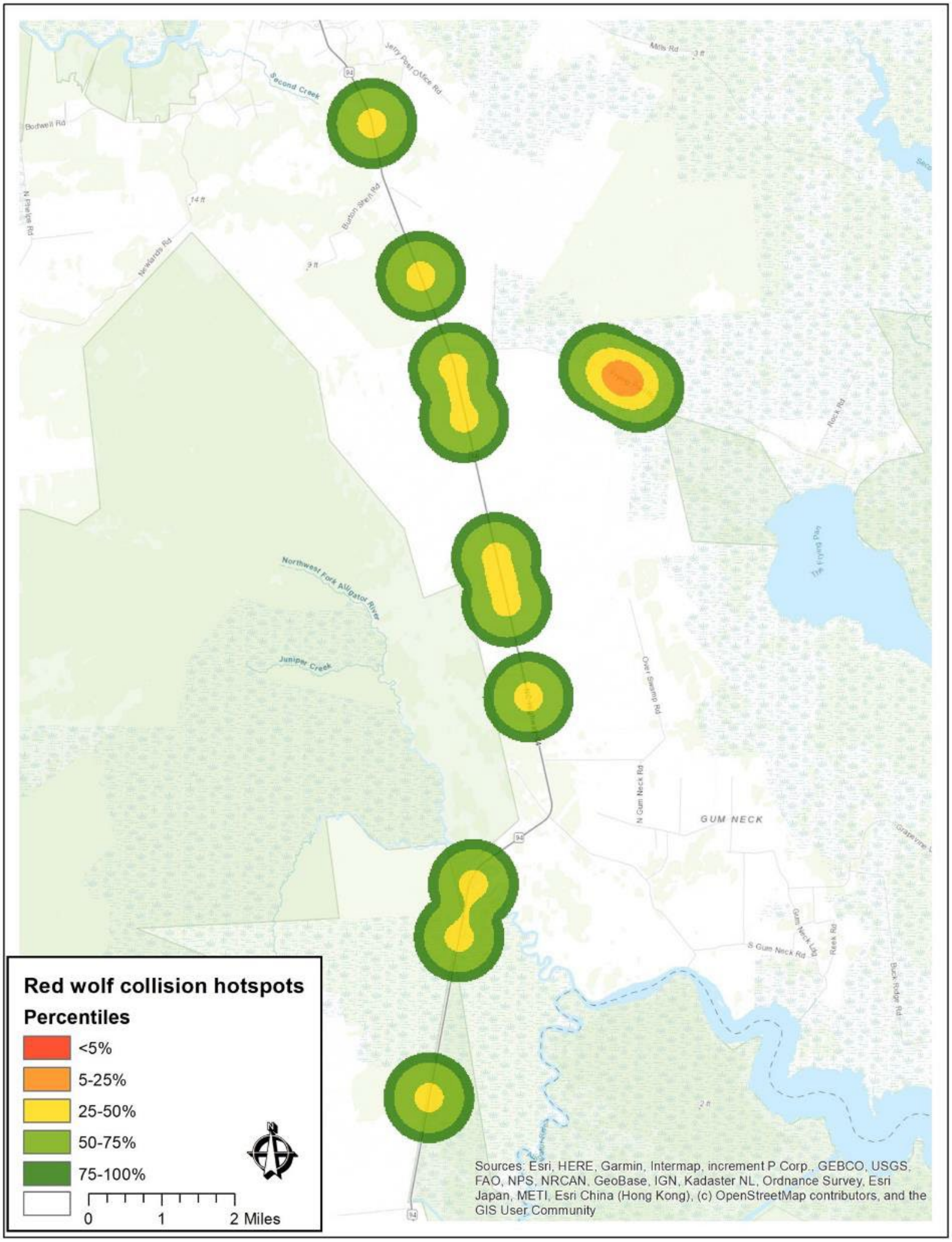

Figure 8: Zoom 4, Hwy 94. Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

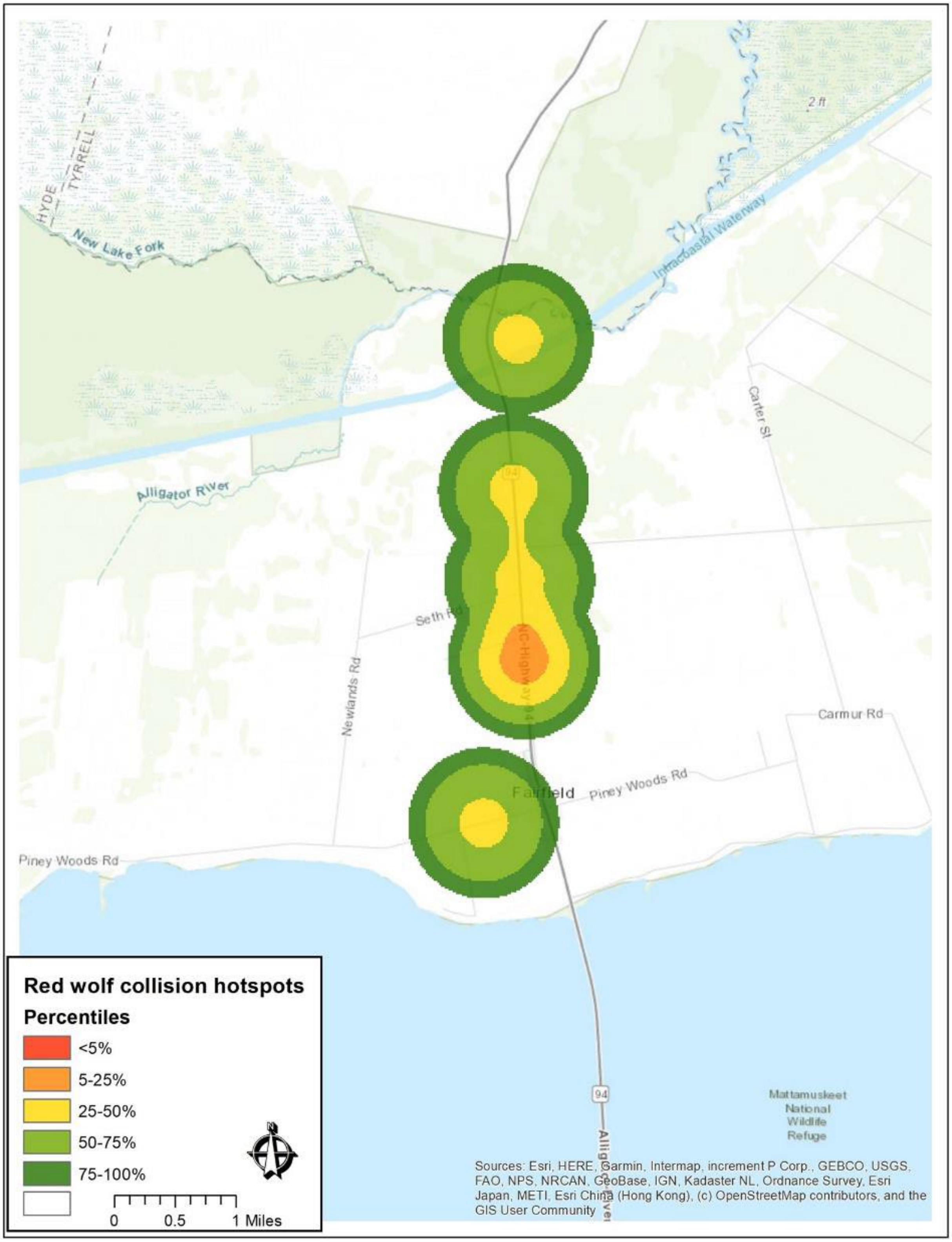

Figure 9: Zoom 5, Hwy 94. Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

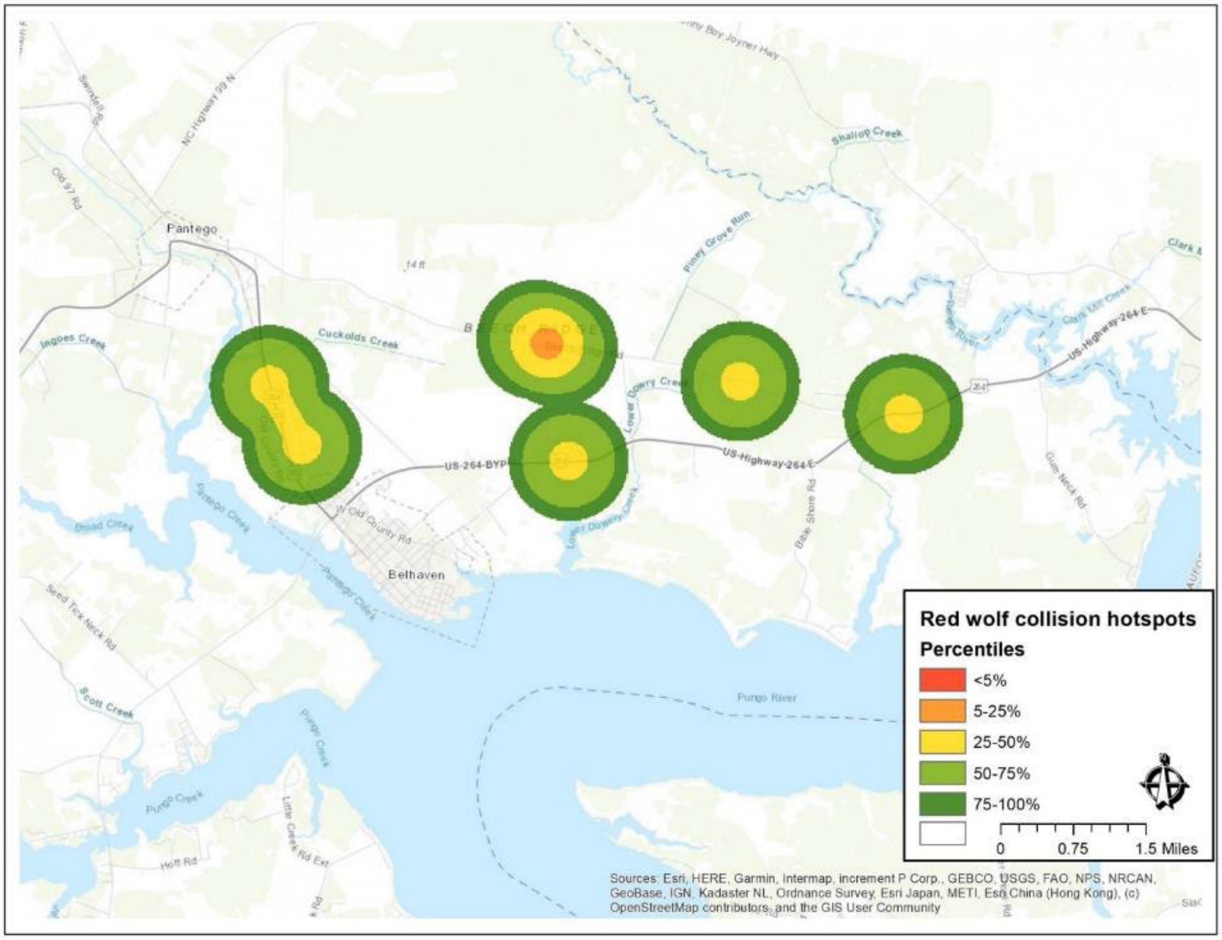

Figure 10: Zoom 6, Beech Ridge Rd. Kernel density hotspot percentiles red wolf-vehicle collisions (1987–2022).

The location of the hotspots is associated with where red wolves have been present the longest and where they have been released (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). Regardless, the location of the red wolf collision hotspots shows that direct road mortality does not only occur along US Hwy 64. Therefore, a possible road reconstruction project of this highway and associated mitigation measures for the red wolf would only address a portion of the direct road mortality problem. If the main objective is to substantially reduce direct road mortality of red wolves, a more integral approach is needed for all highways in the Eastern North Carolina Red Wolf Population (ENC RWP) area. In addition to US Hwy 64, measures are likely most needed along US Hwy 264 and Hwy 94.

4.3. Traffic volume in relation to direct road mortality

Direct road mortality indicates “unsuccessful” crossings and represent a barrier. The prevailing theory is that direct road mortality increases with growing traffic volume, but only up to a several thousands of vehicles per day (perhaps peaking between 2,500 and 10,000 vehicles per day) (Seiler 2003). When traffic volume gets high enough, many animals increasingly chose to no longer cross the highway; the barrier effect disproportionally increases from perhaps around 7,500 vehicles per day and up. As fewer animals attempt to cross, direct road mortality reduces with these higher traffic volumes. Note that there may be profound differences between species in what traffic volume levels start to affect their willingness to approach and cross a highway.

Traffic volume data were obtained for the main roads in the ENC RWP area (Figure 11) (NCDOT 2023). Most of the traffic volume data related to the most recent year the data were available for (2021), but for some minor roads the most recent data were from earlier years. US Hwy 64 has the highest traffic volume of roads in the area, ranging from 8,700 vehicles per day towards the west end of the area to around 4,000 vehicles per day near the coast (Figure 11). Other highways and highway sections in the area had much lower traffic volume, ranging from a few hundred vehicles per day up to about 1,000 or 2,000 vehicles per day. Interestingly, red wolf collision hotspots occurred along both the busiest highway (US Hwy 64, through Alligator River National Wildlife Refuge) as well as with roads with about 1,000 or even just a few hundred vehicles per day (Figure 11).

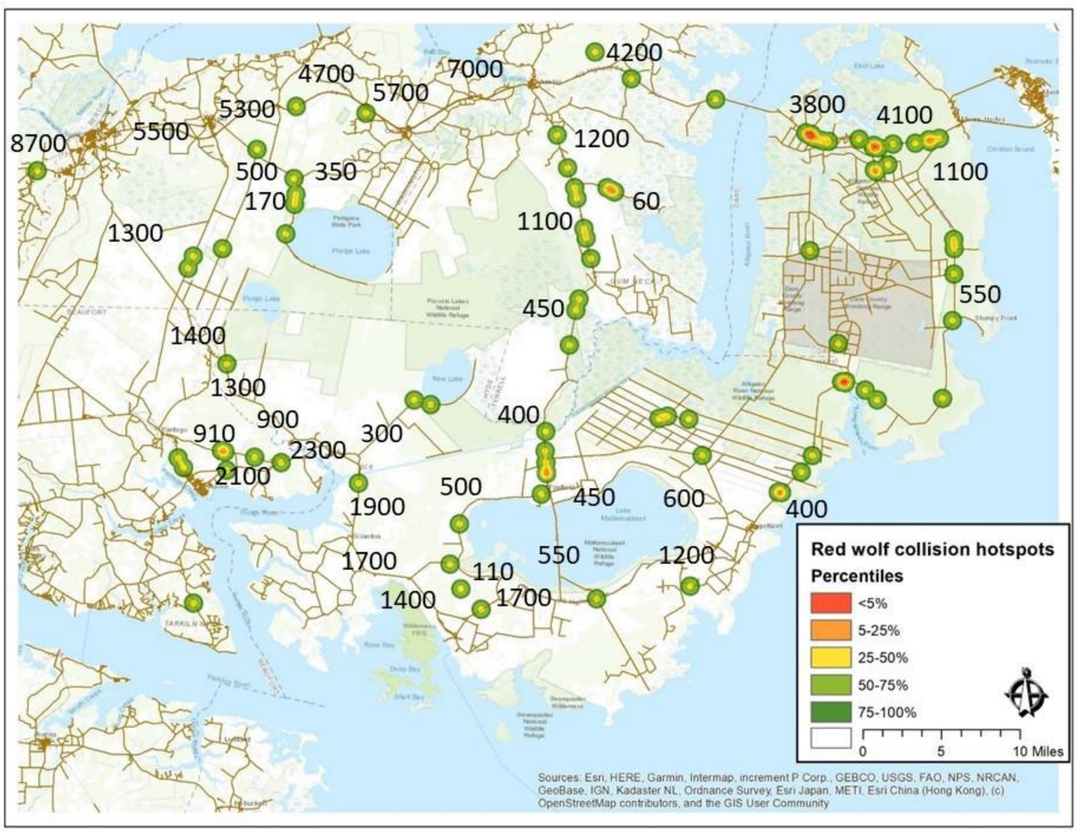

Figure 11: Annual Average Daily Traffic (AADT) projected on the red wolf vehicle collision hotspots. Note that not all roads or road sections have their traffic volume displayed.

All “system roads” and sections of “system roads” (paved roads maintained by NCDOT) that were closest to recorded road mortalities of the red wolf and closest to birth locations (regardless of when these mortalities or births occurred) were selected for more extensive analyses into where red wolf road mortalities occur in relation to traffic volume. These roads have “proven” to be, or be close to, where red wolves are or have been, and these roads are therefore most “susceptible” to direct road mortality of red wolves. A caveat is that the red wolves were never homogeneously distributed across the area and that there were also substantial fluctuations in population size and spatial distribution. This means that not every road section included in the analyses had equal exposure to red wolves.

There were 91 recorded road mortalities for red wolves in total (see Appendix). However, two road mortality records did not have coordinates, and 11 road mortalities were on non-system roads, such as gravel or dirt roads) (Figure 12). This left 78 recorded red wolf road mortalities that had coordinates and that were associated with system roads. Of the selected system roads, each road section was divided in 0.1 mile road segments and each road segment was coupled with the AADT from the most recent year (usually 2021, but for some low volume roads the most recent counts were older, up to 2012) (NCDOT 2023). The number of red wolf road mortalities on the system roads was tallied for each of the traffic volume categories shown in Figure 13. The traffic volume category 101-500 vehicles per day had more red wolf road mortalities (N=26, 33.33% of all reported road mortality on system roads) than the other traffic volume categories (Figure 13). Overall, the vast majority of all direct red wolf road mortalities (N= 72, 92.31%, of all reported road mortality on system roads) occurred on roads between 101 and 5,000 vehicles per day (Figure 13). This means that if the total direct road mortality of red wolves is to be substantially reduced in the ENC RWP area, the historic data suggest that the efforts should be focused on roads with a traffic volume between 101 and 5,000 vehicles per day. Efforts aimed at reducing direct road mortality of red wolves along busier roads (>5,000 AADT) in the ENC RWP area would not be an effective strategy. This is likely because of two reasons: 1) higher traffic volume roads may be more of a barrier for red wolves and they may not try to cross these busy roads as often, and 2) higher traffic volume roads mostly occur in the extreme west and north of the area where red wolves may have been present less often, and therefore they would not have been trying to cross these roads as frequently.

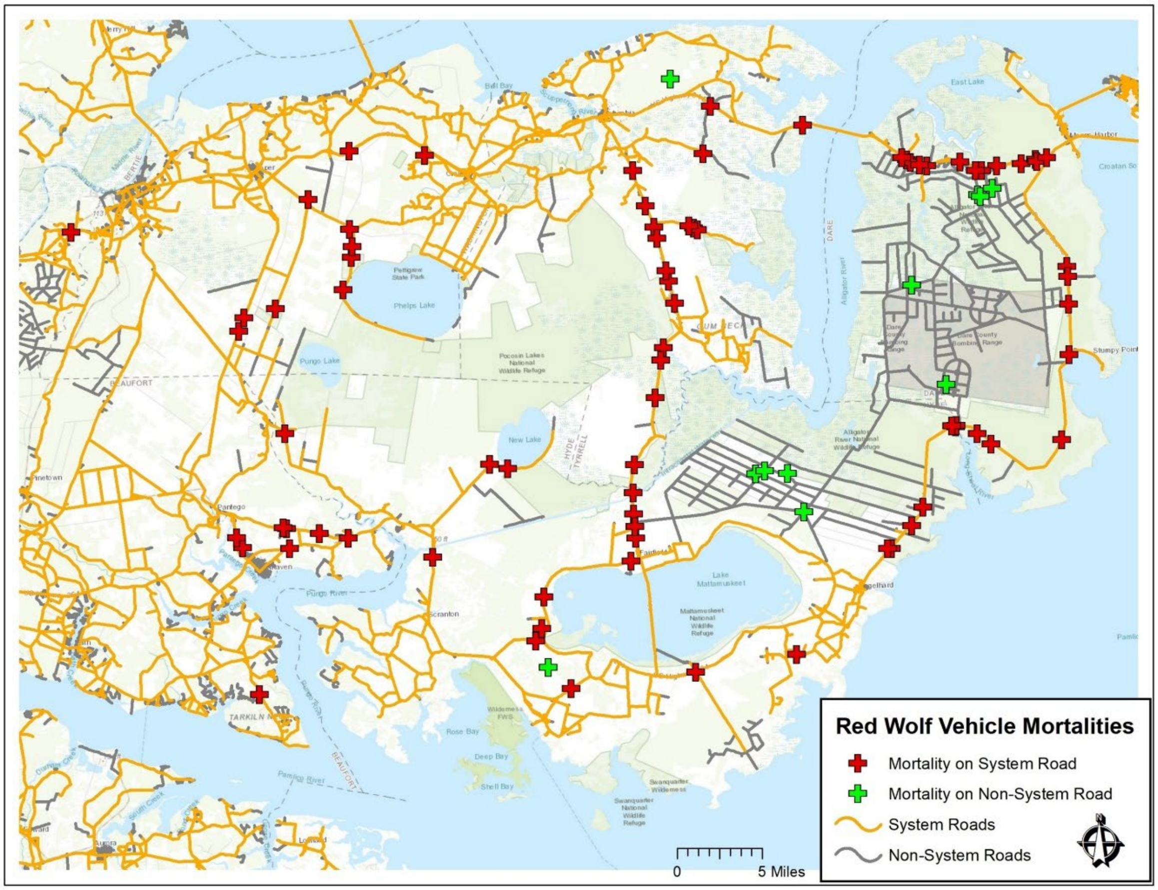

Figure 12: System roads and red wolf road mortalities on systems roads (red) and red wolf mortalities on non-system roads (green).

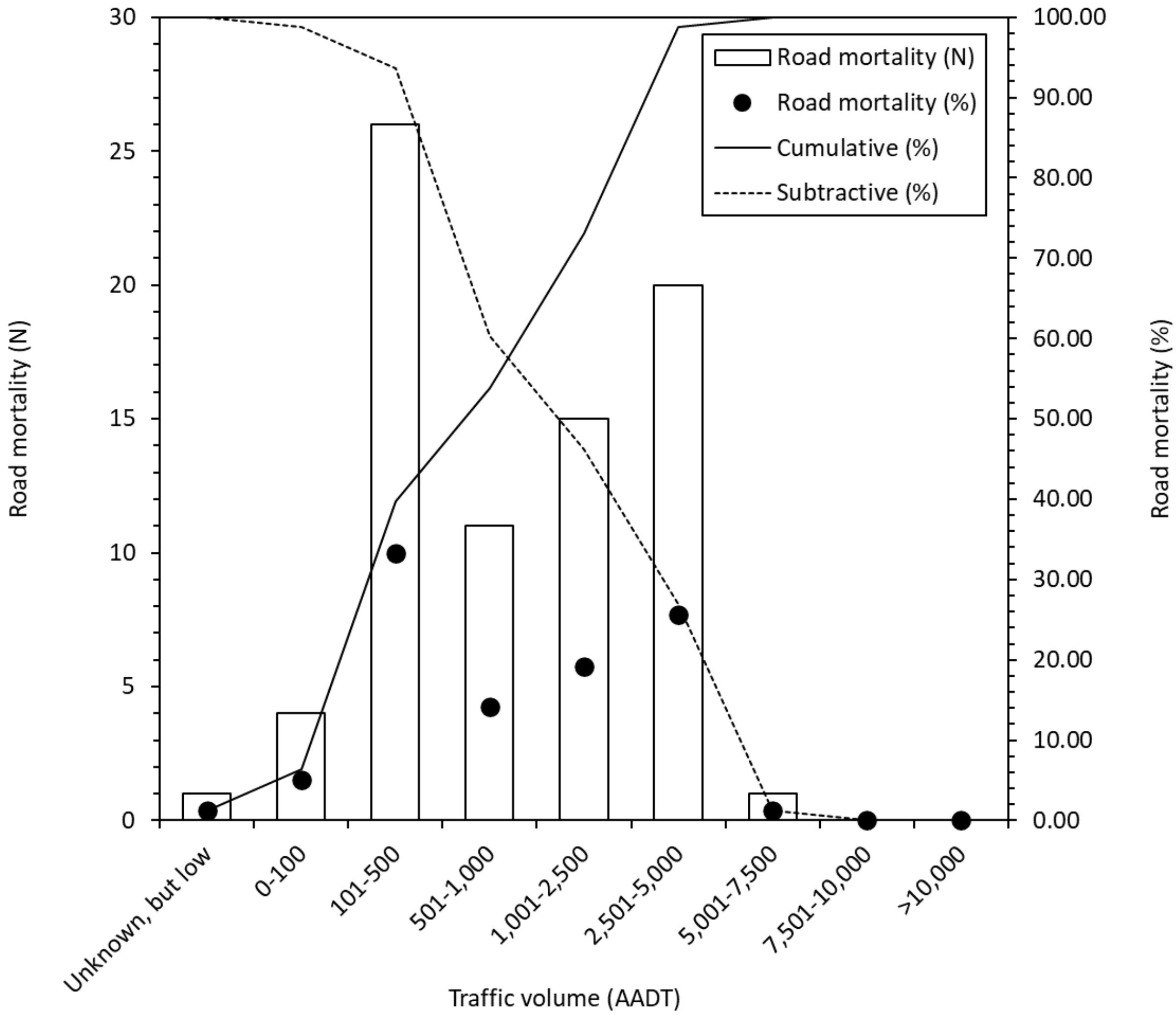

Figure 13: Road mortality counts of red wolves (bars, left Y-axis) for the different traffic volume (AADT) categories and the percentage of the total road mortalities on system roads that these counts represent (dots, right-Y-axis). The two lines illustrate what percentage of mortalities would be addressed if mitigation measures would start with either the highest or lowest volume roads.

The selected road segments were divided in 0.1 mile road segments and each road segment was coupled with the traffic volume (AADT) from the most recent year (usually 2021, but for some low volume roads the most recent counts were older, up to 2012) (NCDOT 2023). Each 0.1 mile road segment was assigned a traffic volume category (Figure 14). The number of 0.1 mile road segments for each traffic volume category was tallied, differentiating between road segments that had recorded red wolf road mortalities, and road segments that did not have recorded red wolf road mortalities. This allowed for the calculation of the proportion of road-killed red wolves for each traffic volume category compared to what would be expected if traffic volume had no impact of red wolf road mortality (Figure 14). Roads with 2,501-5,000 vehicles per day had the highest proportion of observed red wolf road mortality by far (Figure 14). There was a factor of 2.34 more red wolf road mortalities for road sections in this traffic volume category than would have been expected if traffic volume did not influence road mortality. This means that implementing mitigation measures along roads with a traffic volume of 2,500-5,000 vehicles per day would be most “efficient” with the highest number of red wolf road mortalities addressed for the shortest mitigated road length. Traffic volume categories with a traffic volume between 0 and 2,500 vehicles per day had red wolf road mortalities that were roughly proportional to their road length (Figure 14). The lowest (“unknown, but low”) and highest traffic volume categories (over 5,000 vehicles per day) had proportionally very few road mortalities of red wolves, and this is where mitigation measures would be most “inefficient” with the fewest red wolf road mortalities addressed for the road length mitigated.

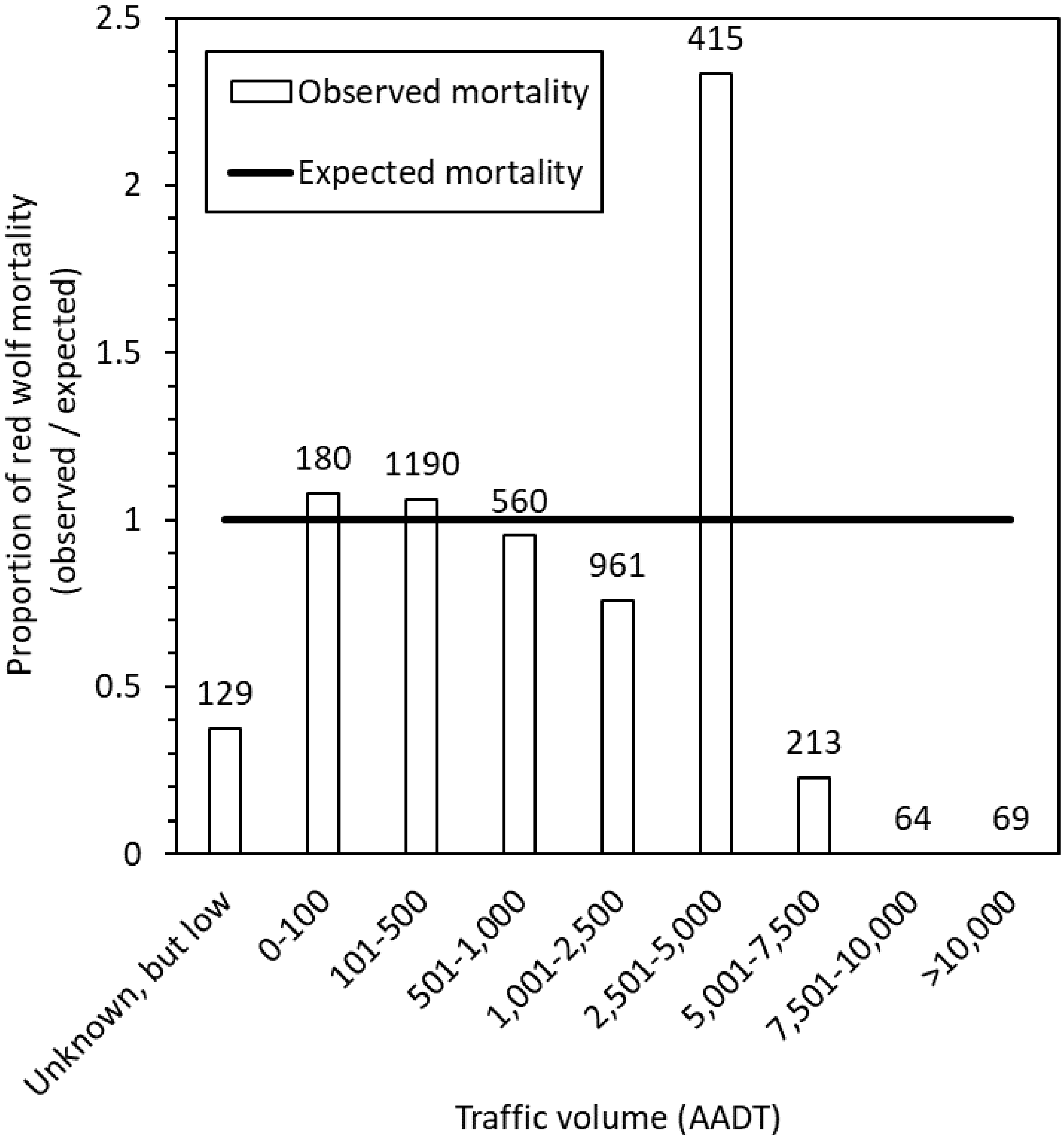

Figure 14: The proportion of observed of direct road mortality of red wolves for each traffic volume category compared to what would be expected if red wolves would be hit proportionally among the different traffic volume categories. The total number of 0.1 mile road segments for each traffic volume category, regardless of whether red wolf road mortality was observed in the 0.1 mile segments, is shown above the bars. This number is equivalent to the sample size for each traffic volume category.

5. HABITAT AND BIRTH LOCATIONS

5.1. Introduction

Before settlement by Europeans, the red wolf was common throughout the eastern and south-central United States and must have occupied a wide variety of habitat types. However, in this chapter the existing knowledge on habitat use of red wolves in the ENC RWP area is summarized in the context of highway crossings.

5.2. Habitat use

Based on Vaughan et al. (2011b) and Dellinger et al. (2013), we know that:

- In general, red wolves were concentrated on higher and drier areas such as upland forests and areas that are now largely agricultural or semi-agricultural, including successional fields.
- In general, red wolves avoid wet habitat such as pocosins, wetlands, and lowland forests.
- Red wolves selected low volume unpaved roads for travel.
- High volume primary roads (paved roads, highways) may be avoided by red wolves.
- Based on GPS collared red wolves, almost all red wolves that approached US Hwy 64 within 164 ft (50 m) successfully crossed to the other side of the road. This indicates that when a red wolf has decided to come close to the highway, it almost always crosses successfully. It appears though that, in general, red wolves avoid the proximity of high volume roads.

5.3. Crossing locations US Hwy 64

Vaughan et al. (2011b) identified important red wolf crossing areas along US Hwy 64.

- Between River Rd and east of Deep Bay Rd.
- Between just east of Columbia and west of Alligator River.

Note that potential important crossing locations along other highways were not investigated (e.g., US Hwy 264 and Hwy 94).

5.4. Birth locations

Highway sections that bisect or that are near the home ranges of breeding pairs are of high importance for mitigation. If one of the breeding adults dies, e.g., because of a vehicle strike, the whole litter may be in jeopardy. In order for the red wolf population to recover, the survival of breeding individuals and their offspring is essential. For this analysis, we investigated where the highest concentrations of birth locations were for red wolves between 28 April 1988 and 8 April 2016 (707 reported birth locations of red wolves in total) (Figure 15).

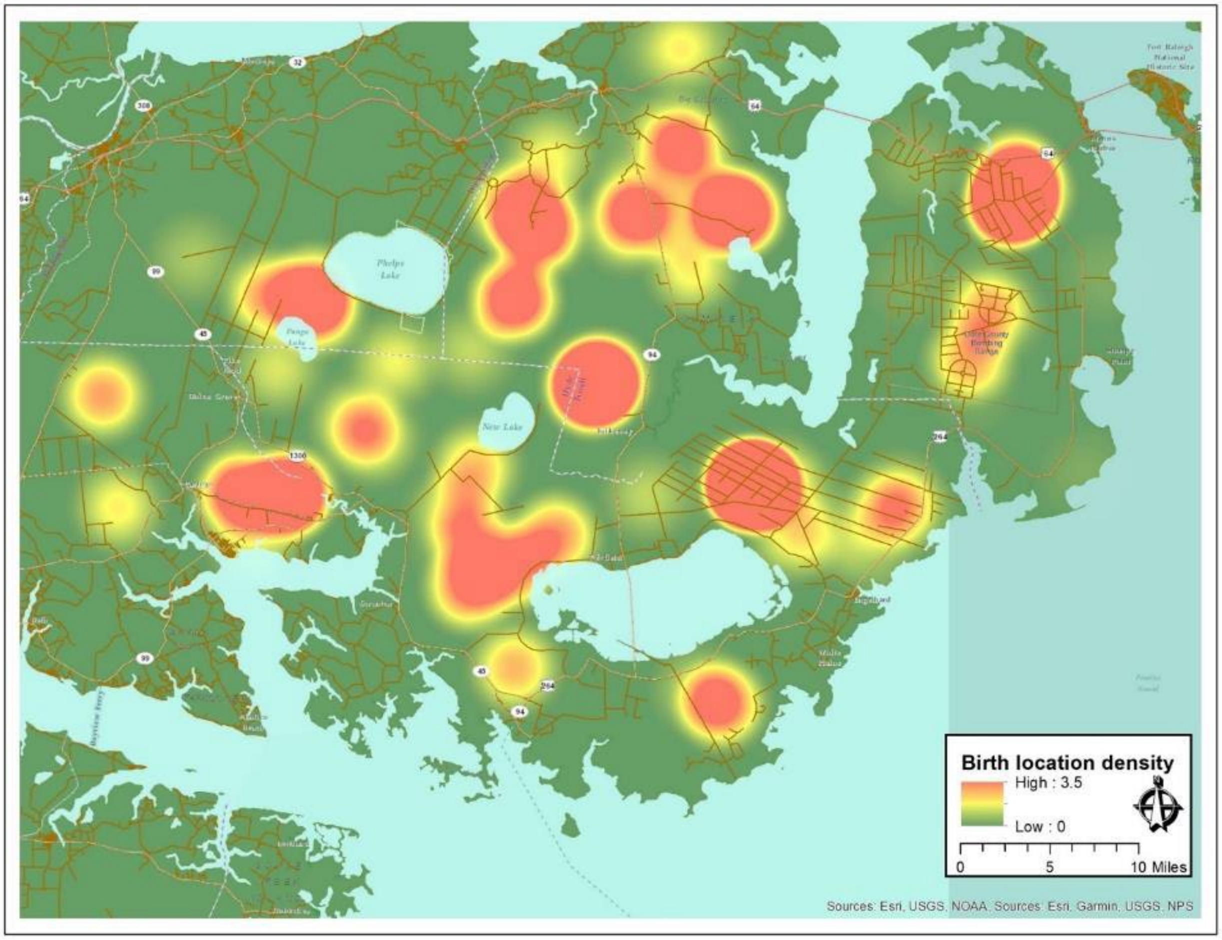

Figure 15: Kernel density hotspot birth locations for red wolves (1987–2022).

Road sections that are “near” high concentration birth locations include:

Along US Hwy 64

- Milltail Rd – just west of the junction with US Hwy 264

Along US Hwy 264

- North of Link Rd – Borrow Pit Rd.
- North of Engelhard
- Near New Holland, south of Lake Mattamuskeet
- East of Belhaven

Along Hwy 94

- North of Frying Pan Rd – south of Frying Pan Rd.
- Around Kilkenny

Note that there are other road sections along lower volume paved roads that are also close to high concentrations of birth locations. Examples are:

- Frying Pan Rd
- Hwy 45, north of Pungo River
- Beech Ridge Rd
- Hwy 94 along west shore of Lake Mattamuskeet
- North Lake Rd along north shore of Lake Mattamuskeet

To examine where highways separate birth locations, we divided the ENC RWP area into smaller areas separated by highways or other paved roads and water (Figure 16). While the boundaries are at least somewhat subjective, it is obvious that there are two large more or less contiguous areas with the highest number of birth location hotspots:

- Pocosin Lakes National Wildlife Refuge and surrounding lands, seven birth location hotspots.
- Alligator River National Wildlife Refuge and the Dare County Bombing Range and the land north-east of Lake Mattamuskeet, four birth location hotspots.

Since the birth location hotspot map is based on all birth locations between 28 April 1988 and 8 April 2016, and since there was a substantial decline in the red wolf population between 2014 and 2022, we can expect most of these birth location hotspots to be historic rather than current. This also means that there is evidence of good habitat quality that allowed for breeding and where dispersing red wolves may be able to find mates, establish territories, and breed successfully. In that context these two areas can form the “source” for colonizing or recolonizing other areas that may be smaller and more isolated.

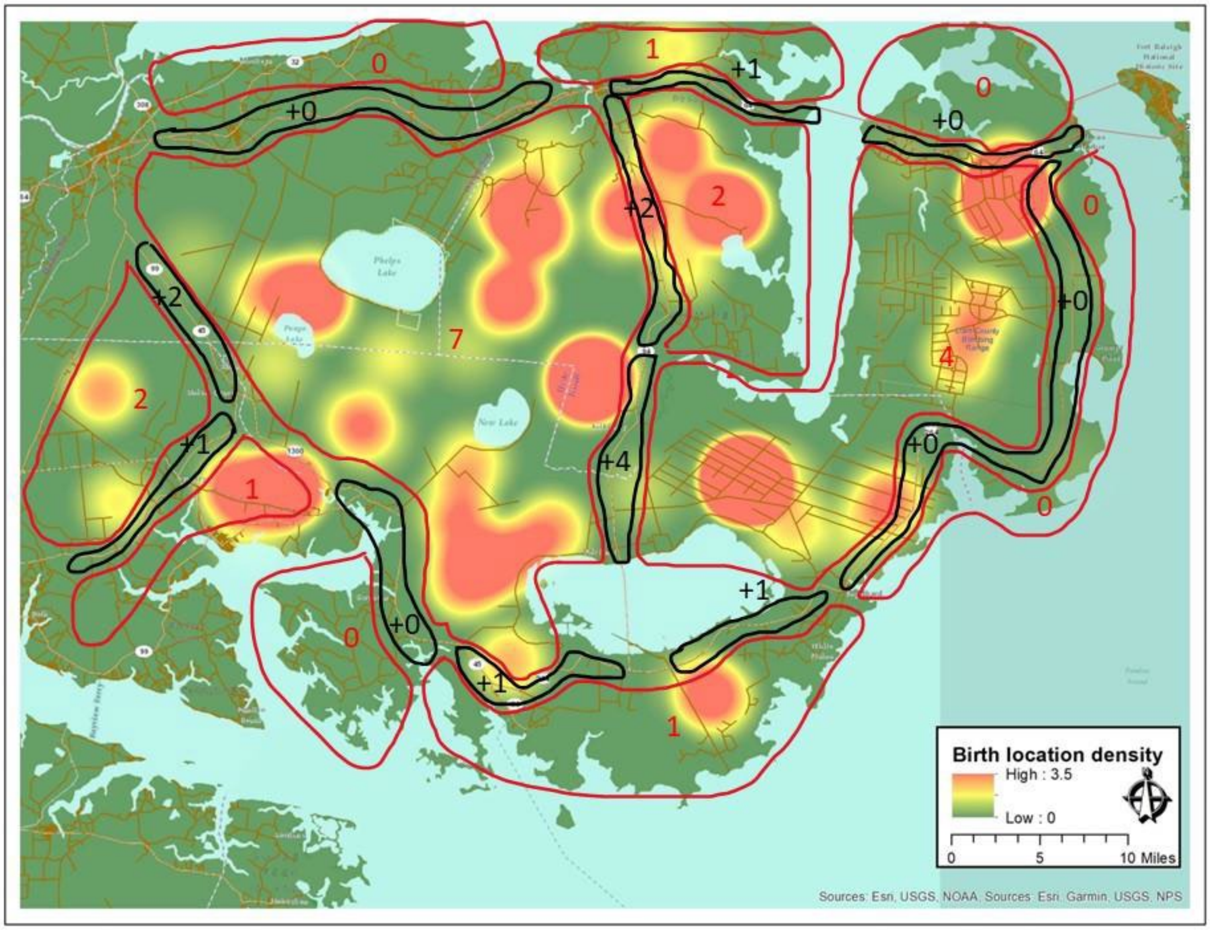

Figure 16: Areas with red wolf birth locations separated by highways and water (red lines) and the number of birth location hotspots (red numbers). The road sections separating these areas are indicated by the black lines and have the lowest number of hotspots on one of the two sides of the road was indicated in black (the numbers with a "+) in front of it.

To examine which system road sections were closest to birth locations, the selected road segments were divided in 0.1 mile road segments. Each birth location was projected on the closest 0.1 mile road segment of a system road. Three search distances were used for birth locations, regardless of the side of the road the birth location was on: 1) up to 500 m, 2) up to 1,000 m, and 3) up to 1,500 m. The number of birth locations projected on each 0.1 mile road segment was tallied, and higher numbers of birth locations were represented by larger circles (Figure 17, 18, 19). The 0.1 mile road sections with the highest numbers of birth locations close to the road (Table 1) can be considered the most dangerous 0.1 mile road segments to breeding red wolves and their offspring, regardless of whether direct red wolf mortality has occurred there in the past. The maps can also be interpreted beyond the 0.1 mile road segments. If there are different 0.1 mile road segments close together with a total high number of projected birth locations, then these road sections may represent a similar danger to breeding red wolves and their offspring. An example is Hwy 94 just north and south of the junction with Frying Pan Rd.

Table 1: Road sections with at least one 0.1 mile road segment that had at least 10 red wolf birth locations projected on it.

Location description	**≤500 m**	**≤1,000 m**	**≤1,500 m**
Frying Pan Rd	X	X	X
US Hwy 64, Miltail Rd area	X	X	X
Beech Ridge Rd	X	X	X
US Hwy 264, landfill area		X	X
SR 1305, northwest of Lake Mattamuskeet		X	X
SR 1304, Turnpike Rd, west of Lake Mattamuskeet			X
SR 1105, near Miles Liverman Cemetery, SE Columbia			X
SR 1311, northeast of Lake Mattamuskeet			X

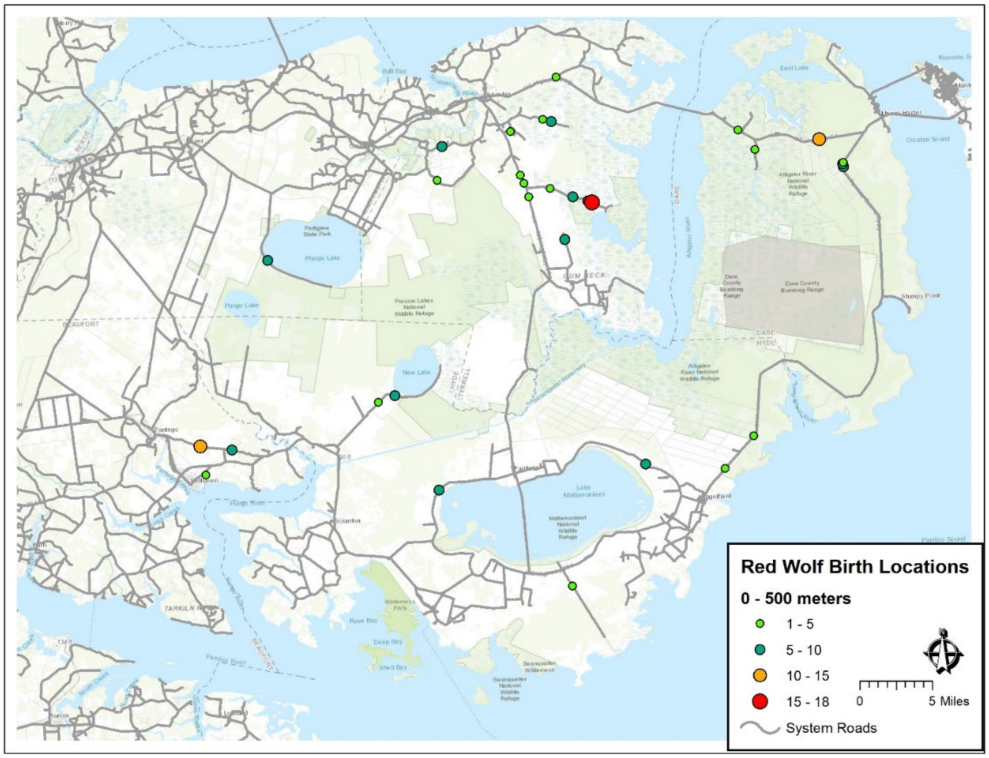

Figure 17: The number of red wolf birth locations projected to the nearest 0.1 mile system road segment, op to 500 m from the road, regardless of which side of the road.

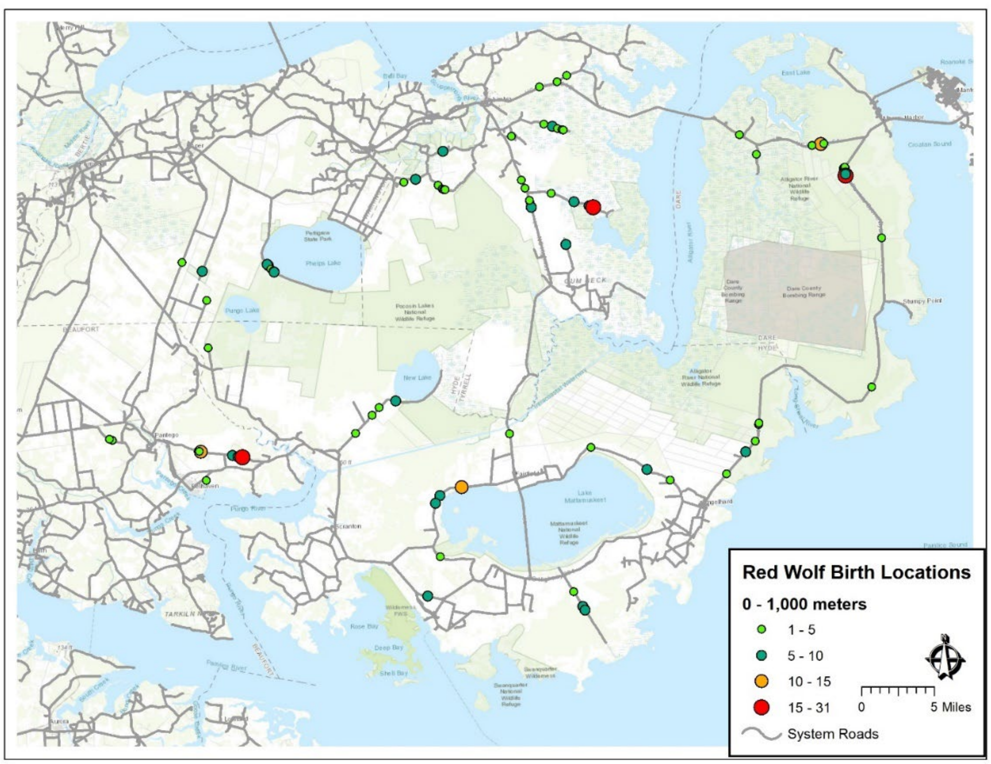

Figure 18: The number of red wolf birth locations projected to the nearest 0.1 mile system road segment, op to 1,000 m from the road, regardless of which side of the road.

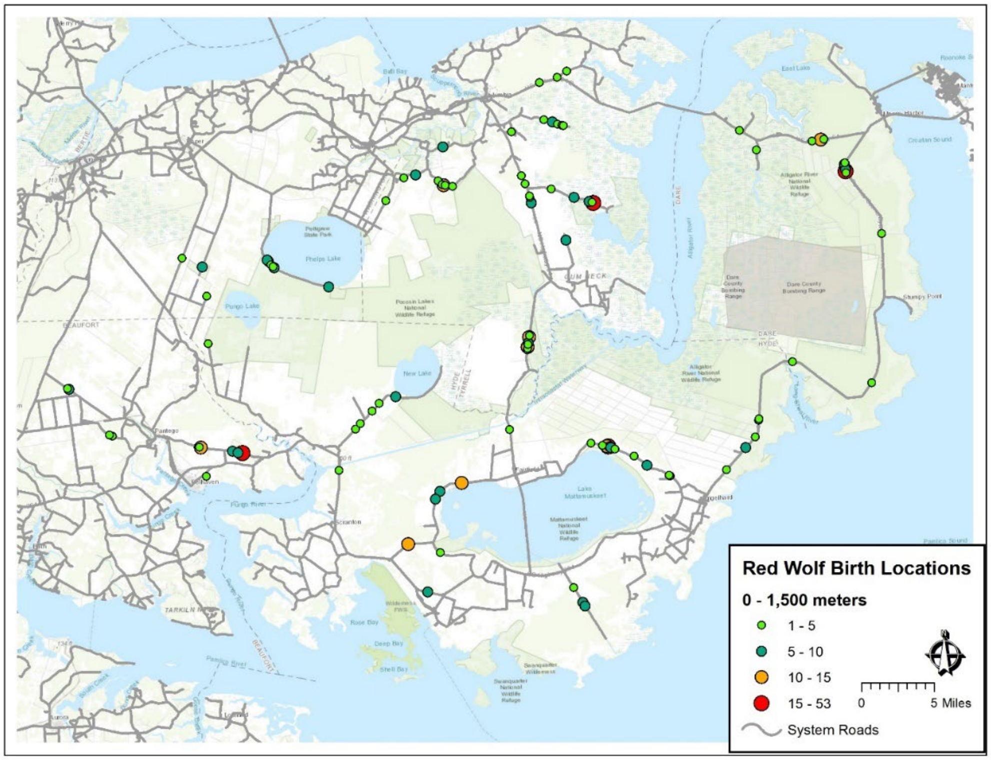

Figure 19: The number of red wolf birth locations projected to the nearest 0.1 mile system road segment, op to 1,500 m from the road, regardless of which side of the road.

6. MEASURES THAT HAVE BEEN IMPLEMENTED FOR RED WOLVES

6.1. Introduction

This chapter provides an overview of measures that have been implemented with the purpose of reducing direct road mortality and improve connectivity across roads for red wolves. We distinguish between measures along highways and measures along gravel and dirt roads on Alligator National Wildlife Refuge. Finally, we discuss the effectiveness of these measures.

6.2. Along highways

Wildlife warning signs

Both static (standard) wildlife warning signs and Variable Message Signs (VMS) have been installed along the highways in area designated for the ENC RWP (Figure 20, 21). The assumed purpose of these signs is to reduce the probability of vehicles hitting and killing red wolves. However, in general, these types of wildlife warning signs have been found to not, or not substantially, reduce the likelihood of collisions with wildlife, especially not if they have been in place for a while (see review in Huijser et al. 2015a, 2021). It is only when warning signs are more specific in time and location (e.g., along seasonal migration routes and animal detection systems) that there is evidence of wildlife warning signs reducing collisions. While animal detection systems can be substantially effective in reducing collisions with large wild mammals (range 33-97%), all other wildlife warning sign types do not, or do not substantially, reduce collisions (a reduction of few dozen percentages at best) (see reviews in Huijser et al. 2015, 2021). Furthermore, none of the warning sign types reduce the barrier effect of the roads and traffic for animals, as they still have to navigate the open unnatural surface of a road and the vehicles that drive on it. However, wildlife warning signs can contribute to a different objective. For example, the VMS signs for red wolves have generally been well received by the community and are considered an effective communication tool for informing local landowners and visitors driving through the area about existence and presence of endangered red wolves (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). These VMS signs are placed on roads in closest proximity to release sites where naïve red wolves are at greatest risk of being hit by vehicles, and these signs are moved as needed to other areas within the ENC RWP when monitoring shows that red wolves are using habitat near roads (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). In this context, warning signs can increase awareness of the problems, but it would be better for signs to be directly targeting increased awareness and building support for measures that address the road mortality problem more substantially.

Figure 20: Static wildlife warning sign for red wolf, US Hwy 64, North Carolina.

Figure 21: Variable Message Sign (VMS) for red wolves, US Hwy 264, Alligator River National Wildlife Refuge, North Carolina.

Reduced posted speed limit
Most sections along the major highways in the area (i.e., US Hwy 64, US Hwy 264, and Hwy 94) currently have a posted speed limit of 55 miles per hour. Around intersections and in areas with houses and driveways, the speed limit is typically lower. While there is currently no reduced posted speed limit in place to reduce collisions with red wolves, it is likely a point of discussion for some people. The following information can help such a possible discussion and decision process. Speed management is often suggested as a strategy to reduce wildlife-vehicle collisions. However, speed management is complex, and it is important to distinguish between three types of "speed":

- *The design speed of a highway:* This is used by engineers who then design the associated road characteristics such as lane and shoulder width, curvature, access density, and sight distance. These characteristics physically allow drivers to drive at a certain speed in a safe and responsible manner.
- *The posted speed limit:* This is the legal speed limit depicted on signs. This is typically a the 85th percentile of the vehicle speeds and should not exceed the design speed of a road.
- *The operating speed of the vehicles:* This is the speed that drivers drive their vehicles at.

Most collisions with large wild mammals happen between dusk and dawn when visibility is limited (Huijser et al. 2008a). However, the design speed, posted speed limit and operating speed of major highways is typically too high and the head lights of vehicles do not shine far enough to detect large mammals early enough to allow drivers to stop their vehicle in time (Huijser et al. 2017). With median headlights (low beam) and a 1.5 second reaction time, drivers can, at a maximum, drive about 40 mi/h (64 km/h) and still avoid a collision (Huijser et al. 2017). Higher vehicle speeds do not allow most drivers with median headlights to avoid a collision with a large mammal on the highway, unless the animal moves out of the way, or unless the driver makes the vehicle depart its lane, which is typically not advisable. Since half the cars have headlights that have a shorter reach, an operating speed of 40 mi/h (64 km/h) would still not allow half the drivers to stop their vehicle in time. To allow (almost) all drivers to stop their vehicle in time, operating speed may need to be as low as 25-30 mi/h (Huijser et al. 2017). This is far lower than the design speed of most roads. Most drivers drive a speed (operating speed) that is close to or higher than the design speed of a rural road (Fitzpatrick et al. 2003, Jiang et al. 2016, Donnell et al. 2018). If the posted speed limit is substantially reduced below the design speed for a rural road section through a sensitive area, and if the design speed remains the same for this road section, the following scenario is likely:

- Most drivers will ignore the lower posted speed limit and continue to drive a speed close to or higher than the design speed of the highway (Riginos et al. 2022).
- Some drivers will adhere to the lower posted speed limit.
- The mix of fast and slow-moving vehicles on a highway is referred to as "speed dispersion" and this is associated with more interaction between vehicles, dangerous driving behavior (e.g., irresponsible maneuvers to overtake slow vehicles) and an overall increase in crashes (Huang et al. 2013, Elvik 2014).

For these reasons alone, it is never a good idea to implement a posted speed limit that is substantially lower than the design speed of a highway. Transportation and law enforcement agencies typically respond to drivers who ignore the posted speed limit and who drive a speed that is close to the design speed of a road by increasing enforcement of the lowered posted speed limit (e.g., through radar measurements of vehicle speed and fining the speeders). If the radar posts are at fixed locations, drivers who travel the road section regularly will quickly learn about the location of the radar posts and lower the speed of their vehicle only in the immediate vicinity of the radar posts. This leads to further speed variation and associated risks, additional use of fuel through braking and acceleration, and the road sections in between the radar posts do not actually have slower moving traffic. Finally, drivers that do get "caught" are likely to experience the situation as "unjust" as one cannot reasonably be expected to drive slow on a highway that has wide lanes, wide shoulders, gentle curvature and long sight distances. This is likely to eventually result in pressure to make the posted speed limit more consistent with the design speed of the road. Suggestions and considerations:

- It is not an effective or wise mitigation strategy to implement a posted speed limit that is substantially lower than the design speed of a highway.
- Only consider lowering the posted speed limit if the design speed is reduced accordingly. Depending on the purpose of a highway, lowering the design speed and lowering the posted speed limit may be in direct conflict with the need for "efficient" transportation and this may therefore not be a viable strategy for most highways.
- For speed management to be substantially effective as a measure to reduce collisions with large mammals for more than half the drivers, the design speed, mandatory speed limit, and actual operating speed of the vehicles at night may need to be 35-40 miles per hour (56-64 km/h) at a maximum (Huijser et al. 2015, Huijser et al. 2017).

Given the information above, reducing the posted speed limit along the major highways in combination with lowering the design speed, is in direct conflict with the need for "efficient" transportation. Therefore, if the objective is to substantially reduce collisions with large wild mammals, speed management is not an appropriate tool for most highways.

Reflective collars

When red wolves have reached a certain age, they are equipped with orange radio collars with orange reflective material on the side of the collar (Figure 22, 23). Methods to potentially increase the visibility of the radio collar, and therefore the red wolves, are being discussed with the engineering department at North Carolina State University (NCSU). Besides allowing hunters to better distinguish between red wolves and coyotes, the reflective material on the collar may also help increase visibility of red wolves to drivers and thereby potentially help reduce the likelihood of a collision. Since beginning the use of the orange reflective material on the radio collars, drivers, including Red Wolf Recovery Program and law enforcement personnel, have relayed that they were able to see the orange reflective material on the collar at night time and felt that it substantially increased the visibility of the red wolf. This may be especially helpful on high speed roads where the reflective material makes the animals visible from a greater distance and allows drives more time and a greater distance to attempt avoiding hitting the animal. This would be mostly through reducing vehicle speed as road departures at high speed (e.g., because of swerving) is associated with a high risk of human injuries and fatalities (Riexinger & Gabler 2020, Roque et al. 2021). While no data are available on the effectiveness of reflective materials in reducing collisions with animals, high visibility reflective vests worn by bicyclists resulted in a 38-47% reduction in crashes (review in Huijser et al. 2021).

Figure 22: Red wolf with a collar equipped with reflective orange material (Image provided by Joe Madison, NC Project Manager, Red Wolf Recovery Program).

Figure 23: Two red wolves filmed with a remote sensing camera at night using infrared lighting on Alligator River National Wildlife Refuge illustrates the reflective material. The red wolf on the left has the reflective material on its collar and the red wolf on the right does not (Image provided by Joe Madison, NC Project Manager, Red Wolf Recovery Program).

Awareness
There are two billboards in the region that were installed by Defenders of Wildlife (a non-governmental organization) to increase awareness of the public about the presence of red wolves in the area (Figure 24). While it is likely that these types of signs increase awareness, they do not, or are unlikely to, reduce the likelihood of collisions with wildlife (see review in Huijser et al. 2015a, 2021). In addition, signs do not reduce the barrier effect of roads and traffic for animals. Other effects to increase awareness of red wolves and what is needed for their conservation include public meetings held twice a year, talks to area groups, and interviews in the media etc. (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program).

Figure 24: Billboard sign for red wolves, US Hwy 64, North Carolina.

6.3. Along roads on Alligator National Wildlife Refuge

Seasonal closure

Some roads (or two-tracks) on Alligator National Wildlife Refuge are seasonally closed to motorized vehicles (Figure 25). While there have been 11 vehicle mortalities recorded for red wolves on non-system roads (usually gravel or dirt roads) (see Chapter 4), vehicle volume and vehicle speed on two-tracks is usually low enough to have no or very few collisions with large mammals, eliminating vehicles during part of the year means that no collisions can occur during those times. Similarly, traffic volume is likely low enough to not have two-tracks be a substantial barrier to large mammals. However, eliminating vehicles can potentially reduce the barrier effect because there is no longer any visual and noise disturbance from vehicles and associated human presence (both inside and outside vehicles). In 2022 and again in 2023, road closures on selected gravel roads frequented by visitors were closed due to their proximity to a red wolf family group (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). These roads were closed in mid-December 2022, then opened on 1 March 2023, then closed again mid-April 2023, and they are intended to be closed through August 2023. While vehicle mortality was not the main concern, these closures serve to reduce the chances of it occurring (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program).

Figure 25: Seasonal road closure sign, Alligator River National Wildlife Refuge, US Hwy 64 North Carolina.

Night-time closure

The roads on Alligator River National Wildlife Refuge are only open to the public during daylight hours (30 minutes before sunrise until 30 minutes after sunset) (Figure 26). This means that there are no vehicles operated by the public during the night when the visibility of wildlife to drivers is at its lowest. This measure likely decreases collisions with wildlife, especially for species who are most active during the night. Eliminating vehicles during the night can potentially also reduce the barrier effect because there is no longer any visual and noise disturbance from vehicles and associated human presence (both inside and outside vehicles)

Figure 26: Daylight use only sign, Alligator River National Wildlife Refuge, US Hwy 64 North Carolina.

Reduced posted speed limit

The posted speed limit on all Alligator River National Wildlife Refuge roads, unless otherwise posted, is 35 miles per hour (Figure 27). In the future the posted maximum speed limit may be reduced further to 25 miles per hour (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). While collisions with large wild mammals still occur at these speeds, vehicles that drive 35 miles per hour or less are substantially less likely to hit a large wild mammal compared to highway speeds (Mastro et al. 2010, Huijser et al. 2017, 2021). However, reduced posted speed limits do not necessarily reduce the barrier effect of the roads and traffic.

Figure 27: Posted speed limit sign 35 MPH, Milltail road, Alligator River National Wildlife Refuge, North Carolina.

No stopping or standing allowed

In the fall of 2022, variable message signs were deployed along selected road sections in an area frequented by red wolves (Figure 28). The signs informed visitors that they cannot stop their vehicles and that they cannot not stand around. This measure was intended to reduce potential habituation of red wolves to vehicles and humans which may cause the red wolves to lose their fear of vehicles and people. Not knowing to stay away from vehicles and people is likely to negatively affect the survival of red wolves.

Figure 28: Wildlife warning sign for the red wolf, "endangered wildlife at risk", "No stopping or standing", Red Wolf, Alligator River National Wildlife Refuge, North Carolina.

Awareness
Awareness and appreciation of wildlife is encouraged through having wildlife refuge roads mostly open and accessible to the public and through encouraging wildlife viewing (Figure 29). To increase public awareness of red wolves, there is a Red Wolf Center near Columbia (Figure 30). The center has an interpretation facility for the public and a viewing area for captive red wolves. In addition, the center has a space where health checks can be conducted on red wolves (Figure 31). Furthermore, there are exhibits on red wolves in other visitor centers in the area: Alligator River National Wildlife Refuge Visitor Center and Headquarters in Manteo, and the Pocosin Lakes National Wildlife Refuge Visitor Center in Columbia (Figure 32). Other measures to increase awareness, including the risk of vehicle strikes, include Red Wolf Teacher Ambassadors that are out on the refuge talking to visitors about red wolves, brochures and signs along trails in the area (Figure 33, 34) and brochures geared toward increasing awareness to the presence of red wolves entitled “Welcome to Red Wolf Country” (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). This information is provided at rest stops and visitor centers as well as sent to people reserving vacation rentals in the Outer Banks as these visitors are likely to drive through areas with wild red wolves (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). However, the effectiveness of education and public information campaigns in reducing AVCs is not known and could potentially be zero (see review in Huijser et al. 2021. Given typical operating speed on most highways (55 miles per hour or faster), the measure is not likely effective on most major highways, especially not in the dark (Huijser et al. 2017). In addition, increased awareness does not reduce the barrier effect of roads and traffic for animals.

Figure 29: Wildlife drive sign, Milltail road, Alligator River National Wildlife Refuge, North Carolina.

Figure 30: Red Wolf Center, Pocosin Lakes National Wildlife Refuge, North Carolina (Image provided by Joe Madison, NC Project Manager, Red Wolf Recovery Program).

Figure 31: Red wolf exhibit, Alligator River National Wildlife Refuge Visitor Center and Headquarters in Manteo.

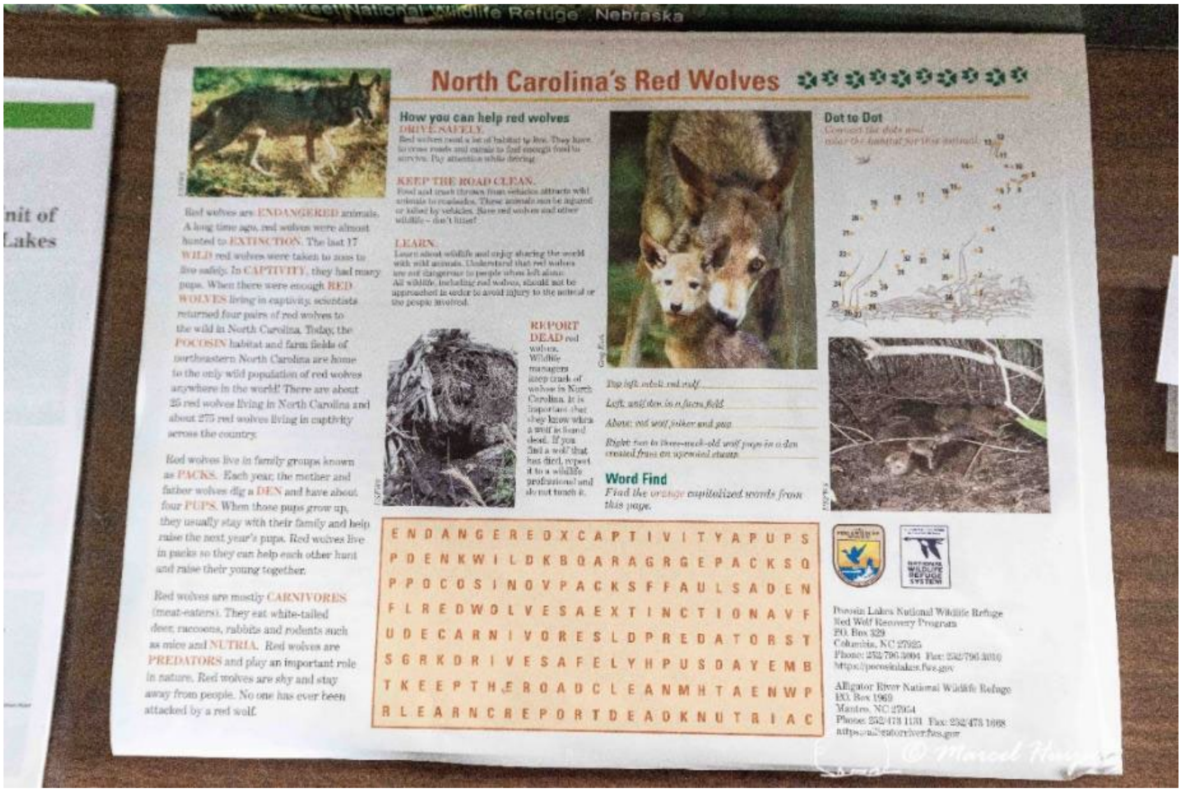

Figure 32: Brochure about the endangered red wolf, Alligator River National Wildlife Refuge, North Carolina.

Figure 33: Brochure about the endangered red wolf, Alligator River National Wildlife Refuge, North Carolina.

Figure 34: USFWS Sign, red wolf country, Red Wolf Recovery Program, Red Wolf, at the visitor center of Pocosin Lakes National Wildlife Refuge, North Carolina.

6.4. Conclusion

Except for radio collars with reflective material, there are currently no measures along the highways in the ENC RWP area that are likely reduce the likelihood of direct road mortality of red wolves. Furthermore, there are no measures in place that reduce the barrier effect of roads and traffic. However, for refuge roads, collars with reflective material, seasonal closure, night-time closure, and a relatively low vehicle speed all likely contribute to a lower likelihood of direct road mortality of red wolves. Seasonal closure and night-time closure also contribute to a reduced barrier effect of the roads and traffic on the refuge, but given that traffic volume is low to begin with and given that the roads are not paved or wide, the barrier effect is unlikely to be a substantial issue on the refuge itself. The role of the warning signs and informational signs is likely limited to increasing awareness of red wolf conservation rather than reducing direct road mortality or decreasing the barrier effect of roads and traffic.

7. SUGGESTED MEASURES FOR RED WOLVES

7.1. Introduction

This chapter describes measures that address the following objectives:

- Provide advice on measures that are likely to substantially reduce direct road mortality for red wolves in the ENC RWP area.
- Provide advice on measures that are likely to provide safe crossing opportunities for red wolves in the ENC RWP area.

The suggested measures are restricted to public roads and highways and do not include refuge roads or private roads.

Apart from removing roads or seasonal or night-time closure of roads, wildlife barriers along highways are the most effective measure to reduce direct mortality of large wild mammals (80-100% reduction) (Huijser et al. 2021). If fences are combined with wildlife crossing structures, the mitigation package can also provide for safe passage. When sufficient numbers of crossing structures are provided at the correct locations, of the correct type and dimensions, they can also reduce the barrier effect of roads and traffic (e.g., Huijser et al. 2016a). While animal detection systems can be similarly effective in reducing direct road mortality of large mammals, their range of effectiveness is much wider, and animal detection systems do not reduce the barrier effect of roads and traffic (Huijser et al. 2021). Nonetheless, this chapter describes both animal detection systems and wildlife fences in combination with wildlife crossing structures, and associated measures.

7.2. Animal detection systems

Animal detection systems use electronic sensors installed along the roadside to detect large animals (e.g., deer size and larger) that approach the road; signs are then activated to warn drivers (Huijser et al. 2015). Most sensors detect any large mammal that approaches, but some systems have been tailored to detect collared animals when they enter a zone close to the highway (Huijser & McGowen. 2003). Regardless of the detection technology, warning signs associated with animal detection systems are very specific in time and place. However, current animal detection systems are more difficult to develop for small or medium sized animal species because they are more difficult to detect reliably. The effectiveness of animal detection systems is variable, but they can reduce wildlife-vehicle collisions with large mammals by 33-97% provided that the sensors detect the target species reliably species, and relay an associated warning sign to drivers (Mosler-Berger & Romer 2003, Huijser et al. 2006, Dai et al. 2009, Gagnon et al. 2010, 2019, Strein 2010, MnDOT 2011, Sharafsaleh et al. 2012). Since the risk of severe crashes increases exponentially with increasing vehicle speed (Kloeden et al. 1997), it is useful to also evaluate the potential effect of activated warning signs associated with animal detection systems on vehicle speed. Drivers tend to reduce their speed somewhat (<5 km/h) (Kistler 1998, Muurinen & Ristola 1999, Hammond & Wade 2004, Huijser et al. 2006, Huijser et al. 2017, Grace et al. 2017) or more substantially (≥5-22 km/h) in response to activated signs of animal detection systems (Kistler 1998, Kinley et al. 2003, Gordon et al. 2004, Gagnon et al.

2010, 2019, Sharafsaleh et al. 2012, Huijser et al. 2017). The greatest reductions in vehicle speed seem to occur when the signs are associated with advisory or mandatory speed limit reductions or if road conditions and visibility for drivers are poor (Kistler 1998, Muurinen & Ristola 1999, Huijser et al. 2017).

Actual and perceived reliability can differ as drivers may rarely see animals on or along the road when the warning signs are activated (Sharafsaleh et al. 2012), or they may see animals in the proximity of the road with the warning signs turned off as the animals are beyond the range of the sensors. Regardless, to inform the driver adequately, it is important that the warning signs are relatively close together. A driver should not pass a warning sign without being able to see and interpret the next warning sign should it be activated. This may require a modification of the guidelines for sign placement which tend to be based on static signs rather than signs that display no message at all unless a danger has been detected. Many animal detection systems have a portion of the warning signs visible all the time (e.g., an additional flashing light is activated after a detection has occurred). However, it is likely best if no message is displayed at all, unless an animal has been detected to minimize the likelihood that drivers ignore activated signs and to avoid oversaturating the roadside with signs. Additional standard signs spaced at relatively great distances may then still address potential liability issues with animals on the road.

Animal detection systems should still be considered experimental, and implementation should be regarded as a high-risk project as many projects fail because of technological, management, financial, or maintenance issues (Huijser & McGowen 2003, Huijser et al. 2006, 2009a, 2009b, 2017, Sharafsaleh et al. 2012, Huijser et al. 2017). Detection systems are experimental regarding the level of certainty that a system will be operating as desired by a particular date - especially in detecting the target species with sufficient reliability - and a relatively wide and variable range of effectiveness in reducing wildlife-vehicle collisions. The latter is probably associated with the different types of detection technologies and the great variability in the signs presented to drivers. Note that animal detection systems do not address the barrier effect of a highway and associated traffic.

While there are no guidelines or standards, animal detection systems are typically only implemented along relatively low volume highways (a few thousand up to perhaps 14,000 vehicles per day at a maximum). For high-volume roads (certainly for highways with more than 15,000 vehicles per day), a physical separation of traffic and wildlife (i.e., through underpasses and overpasses for wildlife) is almost always advisable for two reasons. First, few species or individuals of a species are willing to still cross because higher traffic volumes result in the road and traffic becoming a greater barrier (Seiler 2003). Second, activated warning signs are meant to result in a sudden change in vehicle speed, and this can result in rear-end collisions. This means that animal detection systems become less appropriate when traffic volume increases. Furthermore, animal detection systems are not necessarily less expensive than wildlife fences in combination with wildlife crossing structures and electronic equipment is likely to have a shorter lifespan than fencing material and the concrete and steel associated with crossing structures (Huijser et al. 2009c). The configuration of a road and the surroundings (e.g., curvature, side roads or driveways, line-of-sight, shoulder, topography and surrounding vegetation) can influence the type of sensors chosen as well as the number of sensors and associated costs (Huijser et al. 2009b). Finally, while somewhat hypothetical, activated warning signs may also make poachers more aware of where and when they should target their efforts.

In summary, animal detection systems can be used to reduce the likelihood of red wolf-vehicle collisions. However, many animal detection system projects have failed for a variety of reasons, which means that, compared to wildlife fences and animal detection systems, it is less likely that a substantial reduction in collisions will indeed be achieved. When animal detection systems prove to be reliable and are in place long enough to have their effectiveness evaluated, they can reduce collisions with large wild mammals, similarly to wildlife fences in combination with wildlife crossing structures. However, their range of effectiveness is much wider towards the low end. Traffic volume along US Hwy 64, US Hwy 264 and Hwy 94 are low enough to consider animal detection systems, but if the objective is also to reduce the barrier effect of roads and traffic, then animal detection systems are not appropriate.

7.3. Wildlife fences and associated measures

Wildlife barriers can either be fences or walls, and the latter may be integrated in the roadbed when landscape aesthetics as observed from the road are a concern. However, wildlife fences are far more commonly applied than wildlife walls, especially over long distances.

Effective wildlife fences must be designed with the climbing, digging, and jumping capabilities of the target species in mind, as well as their strength. The primary target species for this project is the red wolf. But there are other large wild mammal species in the area too, and one may decide to improve human safety and reduce direct road mortality for those other large mammal species (coyote and larger) with the same fence. Therefore, one may design a wildlife fence to keep multiple species from accessing highways in the area (Table 2).

Table 2: Potential large wild mammal target species and the recommended wildlife fence characteristics based on existing road ecology projects (adapted from Huijser et al. 2022a).

Species name	Height fence	Post material	Fence material	Dig barrier/ apron	Over-hang	Electric fence or wires
White-tailed deer (*Odocoileus virginianus*)	8 ft	Wood	Mesh-wire	No	No	No
Cougar (*Puma concolor*)[1]	10 ft	Metal	Chain-link	Yes	Yes	Yes
Coyote (*Canis latrans*)[2]	8 ft	Wood	Chain-link	Yes	No	Yes
Gray wolf (*Canis lupus*)[2]	8 ft	Wood	Chain-link	Yes	No	Yes
Black bear (*Ursus americanus*)	10 ft	Metal	Chain-link	Yes	Yes	Yes

[1] Presence in the area is possible but not confirmed.
[2] Potentially similar to red wolf

The recommended height is based on the jumping and climbing capabilities of a species, as well as tolerance or intolerance when some individuals breach the barrier. The material for the fence post depends on whether the species can climb wooden posts (metal recommended) or not (wood recommended), but the substrate (rocks) can also dictate the post material (Figure 35, 36). The fence material is based on the size of a species and whether they would be able to pass through the meshes. A dig barrier is usually a 4-5 ft wide galvanized chain-link fence that is attached to the bottom of the actual fence (Figure 37). The buried fence should extend approximately 3.5 ft (1.1 m) under the ground (Clevenger & Huijser 2011). An overhang is attached to the top of the main fence and angles towards the safe side of the fence (Figure 38). Species or individuals that climb a fence would also have to navigate the overhang to make it to the other side of the fence. Electric fences or electrified wires attached to mesh-wire or chain-link fences can also be considered in the design of a wildlife fence (Figure 39). Finally, a high-tensile top wire is recommended when trees are in the vicinity of the wildlife fence (Figure 40). High-tensile top wires can reduce the damage of a fallen tree and prevent a temporary gap in the fence.

Figure 35. Typical large ungulate fence in North America, 8 ft tall, wooden posts and mesh-wire fence material, US Hwy 93 North, Montana, USA. Note that there is a dig barrier attached to the main fence material (e.g., for canids).

Figure 36. Fence for Florida panther (*Puma concolor coryi*), 10 ft tall, metal posts, chain-link fence material, and overhang or outrigger, SR 29, Florida, USA).

Figure 37. Wildlife fence and dig barrier ("buried fence" or "apron"), Trans-Canada Highway, Banff National Park, Alberta, Canada. The dig barrier in the soil angles (45°) towards the safe side or habitat side; it angles away from the fence and the road on the other side (Clevenger and Huijser 2011). The dig barrier keeps animals from digging under the fence. The dig barrier may consist of a 4-5 ft (1.0-1.2 m) wide galvanized chain-link fence that is attached to the bottom of the actual fence. The buried fence should extend approximately 3.5 ft (1.1 m) under the ground (Clevenger and Huijser 2011).

Figure 38. Outrigger or overhang on a fence for Florida panther (*Puma concolor coryi*), SR 29, Florida, USA. Note that the outrigger faces the safe side, the habitat side of the fence. A longer overhang from chain-link fence material is suggested for red wolf.

Figure 39: Wildlife fence along A28 motorway, near Spier, Drenthe, The Netherlands. The fence is a barrier for medium and large mammal species. The electrified wire is an additional barrier to keep animals out of the fenced road corridor.

Figure 40. Wildlife fence with high-tensile top wire to reduce damage from falling trees, Trans-Canada Highway, Banff National Park, Alberta, Canada.

Based on Table 2, a large mammal fence in the project area should probably have the following characteristics:

- Height: 10 ft
- Fence posts: metal
- Fence material: chain-link
- Dig barrier or apron
- Overhang
- Potentially electrified wires attached to the main fence on the safe side of the fence
- High-tensile wire on top, but adjust or reconsider location in combination with an overhang

An example of a fence that is specifically designed for keeping red wolves in captivity is from the Red Wolf Center in Columbia (Figure 41). This fence is about 10 ft high, has metal posts, chain-link fence material, is dug into the soil, and has a very large overhang, angled towards the holding pen of the red wolves. Fences for red wolves around pens are required to have an angled overhang of 3 feet (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). Coyotes and red wolves can and do go over the fence when the overhang is absent or damaged (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program). This fence design is likely to be a substantial barrier for all large mammal species listed in Table 2.

Figure 41: Wildlife fence for red wolf, Red Wolf Center, Pocosin Lakes National Wildlife Refuge, North Carolina.

Specifically for red wolves, the fence requirements are (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program):

- Height: 8 ft. (2.4 m) vertical fence with the addition of a 3 ft. (90 cm) wide overhang. Total height is approximately 10 ft.
- Fence posts: metal pipes 2 in. (5 cm) diameter, set in concrete.
- Fence material: chain link, 9 gauge, mesh size 2 inches (5 cm).
- Dig barrier or apron: 2-3 ft. (60-90 cm) wide section of chain link fencing. Lace it with smooth wire or hog rings to the base of the vertical fencing. Barrier should come to the fence at an angle to the vertical fence and should be buried 6-12 in. (15-30 cm) below ground level.
- Overhang: same specifications as the vertical fence material, slanted in at a 45-degree angle.

For a wildlife fence to be effective in reducing direct road mortality for large mammals consider the following (based on Huijser et al. 2015b, 2022):

- Design the fence for the target species (see above for the fence design characteristics for red wolves) and have a goal and objectives formulated for its effectiveness (e.g., at least 80% reduction in direct road mortality of the target species inside the fenced road corridor). When there is a discrepancy between the stated objectives and the proposed mitigation measures, either adjust the objectives or the proposed measures. Proceeding with a discrepancy between the stated objectives and the proposed measures almost certainly causes the project to fail.
- Construct and install the fence correctly. Have a road ecologist oversee fence design and installation to reduce the likelihood of design and installation errors. Once installed, installation errors are hard and expensive to correct, or the errors may never be corrected at all. This can severely jeopardize the effectiveness of the mitigation measures. Connections to crossing structures, the installation of dig barriers and measures at access roads, and addressing erosion and sedimentation processes are major concerns.
- Implement the fence on both sides of a highway for at least three miles of road length (Huijser et al. 2016b). This almost always results in 80-100% reduction in direct road mortality of large mammals, but this is largely based on ungulates (i.e., deer, elk) rather than wide ranging carnivores such as red wolves (see next point). Almost always, wildlife fencing should be installed on both sides of a highway, not only on one side (Clevenger & Huijser 2011).
- Cover the road length that may have a concentration of wildlife-vehicle collisions with the target species (i.e., "hotspots") as well as adjacent buffer zones to keep the animals from simply crossing the highway at the fence ends (Ward 1982, Huijser et al. 2015b). The length of the buffer zone is at least partially influenced by the home range size of the target species. For white-tailed deer in North America 1 km long buffer zones have been suggested (starting from each end of the hotspot) (Huijser et al. 2008b). For the red wolf, maximum home range sizes have been recorded at 73-121 km^2 in early autumn to winter and they contract by 40%-63% during whelping and pup-rearing in the spring (Chadwick et al. 2010). Based on a maximum home range size of 97 km^2, and smaller home ranges during the breeding season (51.1% of the maximum home range), and assuming circular shape of their home range, the radius of the home range of a red wolf would be 3,988 m during whelping and pup-rearing in the spring. This means that if the center of a hypothetical circular home range would be on the highway at the edge of a collision

hotspot, red wolves can be expected to regularly travel an additional 3,988 m to either side of the collision hotspot. Thus, fenced road sections for the red wolf should be the length of a collision hotspot plus an additional 8 km (about 5 miles). While these calculations are based on averages and a series of assumptions, it does illustrate that fences designed to reduce direct road mortality for red wolves should be implemented over at least multiple miles of road length (at least 5 miles). Shorter distances are likely less effective in keeping red wolves off the highway during whelping and pup-rearing in the spring. To be effective in reducing direct road mortality for red wolves during other times of year when home range size is larger (for this calculation we use 97 km^2), even longer road sections would need to be fenced (about 11 km (about 7 miles).

- "Fence-end runs" are situations where animals cross the road in high numbers at or near fence-ends (Figure 42). Such fence-end runs are best addressed by having the fence-end at appropriate locations, well away from known movement areas or suitable habitat.
- Fence-end treatments are especially important if the fenced road length is relatively short (e.g., shorter than 3 miles) (Huijser et al. 2016b). To reduce the likelihood of animals accessing the fenced road corridor at a fence-end, consider bringing the fence-ends close to the edge of the pavement, potentially in combination with a wildlife guard or electrified barrier embedded in the pavement (Figure 43, 44) (Allen et al. 2013, Huijser et al. 2022a). To further reduce the likelihood of animals getting on the road at or near a fence-end, consider angling the fence away from the road at the fence-end. This may encourage animals to turn back into the surrounding area, walk back along the fence and potentially find and use a suitable wildlife crossing structure, or it may result in them crossing the road further away from the fence-end. A split fence-end is possible where the other fence-end angles towards the road.
- Note that fences may also need to be implemented over long distances if the objective is to reduce the overall number of collisions rather than just reduce the number of collisions in the fenced road section (Huijser & Begley 2022). It is possible to substantially reduce direct mortality in a relatively short fenced section but not have any benefit on a larger spatial scale as collision locations may have moved rather than truly reduced.
- If the objective is to protect a threatened or vulnerable population or species, the fences road sections should ideally include all roads or all major roads in the area that is occupied by the target species as any unnatural mortality can be considered a threat to the continued existence of a threatened or vulnerable population.
- Minimize the number of access points for side roads and trails along a fenced road corridor. Each access point is a potential weak spot where animals may enter the fenced road corridor. Consider implementing wildlife guards (similar to cattle guards) or electric mats embedded in the roadway to reduce wildlife intrusions into the fenced road corridor at fence ends and at access roads (Figure 45, 46). Wildlife guards or "cattle guards" may be a substantial barrier to ungulates, but not to species with paws (Allen et al. 2013). For species with paws, including bears, canids and felids, electrified barriers may be required, sometimes in combination with a wildlife guard (e.g., Huijser & Getty 2022a).
- Include escape opportunities for wildlife from the fenced road corridor. The main measure available is wildlife jump-outs or escape ramps. However, the effectiveness for large ungulates may need fine-tuning, and the data on jump-out use by canids are very rare (Huijser & Getty 2022b).

- Almost always, include wildlife crossing opportunities that are suitable for the target species, and consider the needs of other species in the area, especially those that are not a target species but for which the fence may also result in a barrier. Solving one problem (direct road mortality, human safety) should not cause another problem (barrier effect for the target species or other wildlife species) (Moore et al. 2021).
- Apart from reducing direct road mortality by keeping animals from accessing the road, fences can also guide wildlife towards safe crossing opportunities (i.e., wildlife crossing structures under or over the road). Connecting crossing structures to wildlife fencing can result in a substantial increase in wildlife use of those structures (Dodd et al. 2007, Gagnon et al. 2010).

Figure 42. Wildlife trail at a fence-end, US Hwy 95, Bonners Ferry, Idaho, USA. This is an indication that there is a concentration of wildlife crossings at the fence-end (a "fence-end run"), potentially resulting in a concentration of collisions at or near the fence-end, just inside or just outside the fenced road section.

Figure 43. Fence-end brought close to the edge of the pavement, protected by Jersey barriers. Also note that there is a wildlife guard embedded in the travel lanes, Alberta, Canada.

Figure 44. Electrified barrier embedded in travel lanes to keep large mammals, including bighorn sheep, out of fenced road corridor, MT Hwy 200, Thompson Falls, Montana, USA.

Figure 45. Wildlife guard at an access road to US Hwy 93S, near Victor, Montana, USA. This type of wildlife guard is less suited for pedestrians and cyclists.

Figure 46. Electrified barrier, designed for low traffic volume and low traffic speed, on top of a wildlife guard at an access road to US Hwy 93S, near Ravalli, Montana, USA.

There likely are other medium-sized mammal species (e.g., bobcat), reptiles (e.g., turtles, snakes, lizards) and amphibians (e.g., frogs, toads, salamanders) in the area that one may choose to also substantially reduce direct road mortality for. This may be especially relevant for species that are associated with the canals, rivers, lakes, and sounds canals that are adjacent to many of the highways (Figure 47, 48). These species or species groups include a wide range of amphibian and reptile species (including American alligator (*Alligator mississippiensis*)) and aquatic or semi-aquatic mammals (e.g., North American river otter (*Lontra canadensis*)). Other species groups that may require mitigation measures include birds, perhaps especially at bridges over rivers and sounds (Figure 49, 50) (Bard et al. 2002, Shwiff et al. 2003). Barrier designs for small to medium-sized mammals, amphibians and reptiles are also species-specific or specific to the species group, but they can be integrated in a fence that is designed for large wild mammals (Clevenger & Huijser 2011, Huijser et al. 2022a) (Figure 51).

Figure 47: US Hwy 64 and adjacent canal, Alligator River National Wildlife Refuge, North Carolina.

Figure 48: North American river otter (*Lontra canadensis*) roadkill, US Hwy 64, east of Columbia, North Carolina.

Figure 49: Wildlife warning sign low flying birds, reduced speed limit, US Hwy 64 William B. Umstead Memorial Bridge, across Croatan Sound, Manteo, North Carolina.

Figure 50: Metal poles attached to bridge to reduce bird-vehicle collisions by making the birds fly higher, State Road A1A, Sebastian Inlet State Park, Florida.

Figure 51. Wildlife fence for amphibians (e.g., common toad (*Bufo bufo*)), medium sized mammals (e.g., Eurasian badger (*meles meles*)) and large ungulates (e.g., roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*)) at ecoduct Woeste Hoeve A50 near Apeldoorn, The Netherlands.

7.4. Wildlife crossing structures

The type (underpass vs. overpass), the approach slope of the structure, the dimensions (width, height) and the associated habitat inside or on top of the crossing structure should be based on the biological requirements and behavior of the target species as well as the surrounding landscape (Table 3-4). Different species are more or less likely to use certain types and dimensions of wildlife crossing structures. For a crossing structure type and dimension to be considered suitable for a species, the likelihood that the structure will be used by an animal that approaches the structure should be "high". While there are no established minimum norms for acceptance, selecting a structure type and dimensions that have a high acceptance rate (perhaps at least 70-80%) for the target species is logical. In this context it is important to remember that having observed "use" by a species does not mean that it is defensible to claim that that that structure type and its associated dimensions are "suitable"; even a structure with a very low acceptance rate still has some "use". By definition, a crossing structure that is "suitable" for the target species is much more likely to be found effective in reaching objectives related to the connectivity than a crossing structure that may be "used" but that may not have a high acceptance rate.

Data on acceptance (and thus suitability) are not common (but see e.g., Purdum 2013. Huijser et al. 2019, Denneboom et al. 2021), and they are not available for all large mammal species in the project area of the report. Therefore, published data on structure types and their acceptance by the large wild mammal species in the area (i.e., coyote size and larger) were supplemented by "use" data (Table 4). Red wolf is the most important target species for this project, but it makes sense to have these crossing structures also be functional for other large wild mammal species in the area (Table 4). Unfortunately, there is no data available on the suitability of different types and dimensions of crossing structures for red wolves in the region (McCollister & van Manen 2010, Vaughan et al. 2011b). Therefore, we also reviewed the suitability of different types of crossing structures for coyote and gray wolf, which are two species that may be most similar in their behavior to the red wolf (Table 4). However, based on their ecology red wolves are likely more similar to gray wolves than coyotes (Pers. com. Joe Madison, NC Project Manager, Red Wolf Recovery Program).

Coyotes readily use large mammal and medium mammal underpasses including box culverts (Ng et al. 2004, Donaldson 2007, Huijser et al. 2016a, Ford et al. 2022). In general, coyote activity by hour of day at crossing structures is similar to their activity patterns in the back country (Barrueto et al. 2014). Coyotes use crossing structures at all hours of the day with no apparent preference for day or night (Barrueto et al. 2014). Human co-use of a structure did not seem to affect use by coyotes (Barrueto et al. 2014). Gray wolves are more demanding and only wildlife overpasses and open span bridges are used regularly (Kusak et al. 2009, Ford et al. 2022). Crossing structures that were high, wide, and short in length (from the animal's perspective) were used most frequently by gray wolves (Clevenger & Waltho 2005). Gray wolf use of narrower (<30 m) crossing structures was unstable over time, but use of wider crossing structures seemed to increase with the age of the structures (Ford et al. 2022). In general, gray wolf activity by hour of day at crossing structures is similar to their activity patterns in the back country (Barrueto et al. 2014). Gray wolves use crossing structures at all hours of the day, but most frequently between dusk and dawn (Barrueto et al. 2014). However, human co-use of a structure is associated with higher use by gray wolves at night and lower use during the day, suggesting a negative impact of human presence on crossing structure use (Barrueto et al. 2014). In summary, coyotes use smaller crossing structures than gray wolves, coyotes use them similarly at all hours of the day whereas gray wolves use the structures predominantly at night, and coyotes are less sensitive to human disturbance than gray wolves.

Table 3: Crossing structure types and dimensions.

Safe Crossing Opportunity type	**Indicative dimensions (as seen by the animals)**	**Image**
Wildlife overpass	50-70 m wide	
Open span bridge	12-30 m wide, ≥5 m high	
Large mammal underpass	7-8 m wide, 4-5 m high	

Safe Crossing Opportunity type	**Indicative dimensions (as seen by the animals)**	**Image**
Medium mammal underpasses	0.8-3 m wide, 0.5-2.5 m high	
Small-medium mammal pipes	0.3-0.6 m in diameter	

Table 4. Suitability of different types of mitigation measures for selected large mammal species (for 2-3 lane highways [25-35 m (82-115 ft)] wide road without median).
● Recommended/Optimum solution; (●) Likely, but no data, ⭘ Likely marginal or somewhat possible if adapted to species' specific needs; ⊗ Not recommended; ? Unknown, more data required; — Not applicable (Clevenger & Huijser 2011, O'Brien et al. 2013, Ford et al. 2017, Huijser et al., preliminary data; Clevenger, unpublished data).

Species	**Wildlife overpass**	**Open span bridge**	**Large mammal underpass**	**Medium mammal underpass**	**Small-medium mammal pipes**
Cougar (*Puma concolor*) [1]	●	●	●	⊗	⊗
Coyote (*Canis latrans*)[2]	●	●	●	●	
Gray wolf (*Canis lupus*) [2]	●	●	⭘	⊗	⊗
White-tailed deer (*Odocoileus virginianus*)	●	●	●	⊗	⊗
Black bear (*Ursus americanus*)	●	●	●	⊗	⊗

[1] Presence in the area is possible but not confirmed.
[2] Potentially similar to red wolf

If red wolves indeed behave similar to gray wolves, structures that are most likely suitable include open span bridges, and wildlife overpasses (Table 4) that would not have human co-use. These structure types are also suited for other large wild mammal species in the area (Table 4). If red wolves behave similarly to coyotes - which, is less likely - large and medium mammal underpasses would also be suitable, and potentially also have human co-use. However, medium mammal underpasses are definitely not suitable for the other large wild mammal species listed in Table 4. In addition, if the crossing structures must be functional for red wolves, then wildlife overpasses and overspan bridges are the choice that will likely contribute to reaching the desired level of connectivity for red wolves. Large mammal and medium mammal underpasses may or may not be readily used by red wolves and if only these types and dimensions of crossing structures are provided, the crossing structures may well fail to provide the desired level of connectivity for red wolves. Therefore, wildlife overpasses and overspan bridges without human co-use are recommended for red wolves for the roads in the project area. Small underpasses may also be provided, but they would be targeted at other species, and not at the red wolf.

A very gradual approach to an underpass and overpass (perhaps 10-15% at a maximum) is recommended. This may be especially relevant in open and flat landscapes compared to landscapes with lots of cover and topography. Gradual approaches may impact natural vegetation. However, the vegetation on the approaches may be restored after construction, and the disturbance is only once. The structure itself may only have a lifespan of 75-80 years (Huijser et al. 2009c). Therefore, only the soil and vegetation on top of an overpass or at an underpass may be disturbed each time the structure is replaced.

Both wildlife overpasses and underpasses may be considered for the roads in the ENC RWP area. If underpasses are considered, the design of underpasses built for in Florida, primarily for the Florida panther, may be also applicable for the roads in the ENC RWP area (Figure 52, 53, 54). The roadbed is elevated on the approaches, followed by a bridge of about 119 ft (36 m) wide and 1=-13 ft (3-4 m) high (Foster & Humphrey 1995). Many road sections in the ENC RWP area have a canal adjacent to the road, similar to some of the structures for the Florida panther in South Florida. Consider making the bridge across canals the same width as the wildlife crossing structure under the road rather than having much narrower bridges across canals.

Figure 52: Wildlife underpass for Florida panthers (*Puma concolor coryi*), about 119 ft (36 m) wide (but only 21-26 m wide at grade level) and about 10-13 ft (3-4 m) high, just after construction in 1998, SR 29, Florida, USA.

Figure 53: Wildlife underpass for Florida panthers (*Puma concolor coryi*) (on the left, under the road), and a wildlife bridge across canal leading up to the underpass (on the right), SR 29, Florida, USA.

Figure 54: Wildlife underpass for Florida panthers (*Puma concolor coryi*) (to the right, outside of image) and a wildlife bridge across canal, SR 29, Florida, USA. Note that the posts on the bridge block illegal use of motorized vehicles such as ATVs.

8. SITE REVIEWS

8.1. US Hwy 64 near Alligator River National Wildlife Refuge

Note: many of the remarks for this location are also valid for the other road sections.

- This area is mostly agricultural or early succession field with forest and dispersed buildings along the road corridor.
- This road section is one of the busiest road sections in the area (3,800-4,100 AADT) and is perhaps of strategic importance for economic development of the Outer Banks and as an evacuation route for hurricanes. The highway cuts through portions of Alligator River National Wildlife Refuge. This is the most likely highway section in the area to be upgraded in the area. When this happens, it would be advisable to make mitigation measures an integral part of the reconstruction project. This is where ref wolf road mortality is considerable, where mitigation measures would be most efficient (Chapter 4), and where there are birth locations relatively close to the road (Chapter 5).
- Road reconstruction and making a 2-lane road into a 4-lane road will result in a wider footprint and habitat loss. Of specific concern are the canals and the habitat they provide for semi-aquatic and aquatic species (e.g., otters, turtles, amphibians).
- A controlled access 4-lane highway will have much fewer access points to the surrounding areas. Where appropriate, consider the use of frontage roads to minimize access points, and consider having existing buildings and driveways fenced in as part of the fenced road corridor. Minimize the number of access points to Alligator River National Wildlife Refuge. A theoretical example of what that could look like is shown in Figure 55. Access points are almost always weak points in the fence, even if they are mitigated with a wildlife guard and an electrified barrier.
- To reduce direct road mortality of red wolves, implement a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length of the highway (west end at the bridge across Alligator River, east end at Manns Harbor. To be effective at reducing direct road mortality of wide-ranging species, mitigation measures need to be implemented at a large spatial scale. For red wolves, based on the size of their home range, the minimum length for a mitigated road section is 5-7 miles, and if there is suitable habitat, the fence should be extended well past the end of the suitable habitat. In reality, effective mitigation will require road sections with wildlife fences that are much longer than 5-7 miles. Implement the fence on both sides of the highway.
- In general, it is considered bad practice to only implement wildlife fences. In general, wildlife fences should be combined with wildlife crossing structures that are in the correct locations (Figure 55) and are of the right type and dimensions for the target species that may be affected by the road, traffic, and the wildlife fence.
- Specifically for red wolves, consider 1 or 2 structures that are specifically designed for the red wolf. These are most likely underpasses that are at least about 30 m wide and 3-4 m high). While wildlife overpasses are also suitable, high ground water levels and shortage of fill will likely be challenging. An advantage of overpasses is that they may also span the canals adjacent to the highways. Underpasses will likely require the build-up of the roadbed on the approaches to the underpass, which also requires fill. The underpass should preferably be an overspan bridge without supports. If support is needed, they should be pillars rather than walls to preserve the lines of sight under the structure as much as possible. Consider one

structure near River Rd and Buffalo City Rd. (Figure 55, 56, 57) and one east of Milltail Rd. (Figure 55, 58, 59). Both locations have a history of red wolf crossings (and direct road mortality) and both locations have a history of a concentration of birth locations. The road length of US Hwy 64 through Alligator River National Wildlife Refuge is about 12-13 miles. Given a home range diameter of about 5-7 miles, this would suggest that potentially 2 packs would be present, each would have 1 suitable crossing structure in their territory. This would make the area north of the highway accessible to red wolves. However, facilitating dispersal of red wolves north of US Hwy 64 is not the main objective for this road section; there is no historic evidence for the presence of birth locations in Alligator River National Wildlife Refuge north of US Hwy 64 as the area may be too small and not may not have sufficient prey (wetlands, forest).

- Additional structures are likely required along this road section for other species such as white-tailed deer and black bear. However, these species likely require smaller structures than what is needed for the red wolf. There are existing plans to rebuild the bridge across the Alligator River (west of Alligator River National Wildlife Refuge (Figure 55, 60). It would be good practice to have that new bridge span semi-aquatic and terrestrial habitat on the shore. A height of 10-13 ft (3-4 m) is recommended. Note that the current structure is not nearly tall enough and does not span enough dry ground to function as a meaningful crossing structure for large terrestrial mammals.
- Rather than selecting locations where existing unpaved roads approach US Hwy 64, consider bridges across the canals as approaches for the crossing structures. This allows for fewer restrictions when identifying the exact location of crossing structures for the red wolf. Consider restricted access to an area around a structure on either side of the road to minimize disturbance to red wolves that may be approaching or leaving the structure. Consider implementing rocks or posts that block (illegal) use by ATVs or other vehicles of the structure. Consider making the bridge across a canal the same width as the wildlife crossing structure under the road.
- Use wildlife jump-outs or escape ramps.

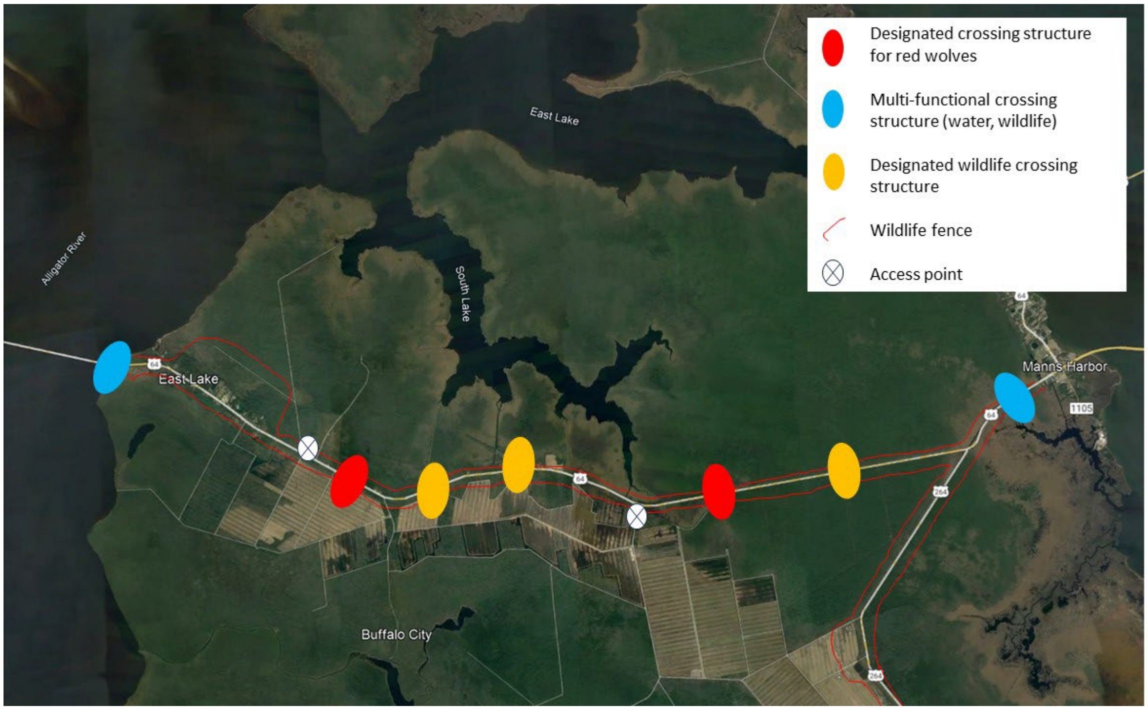

Figure 55: US Hwy 64, suggested crossing structures, wildlife fence, and access points, Alligator River NWR, North Carolina.

Figure 56: US Hwy 64, near Lake Neighborhood Rd, North Carolina.

Figure 57: US Hwy 64 and adjacent canal at Buffalo City Rd., Alligator River National Wildlife Refuge, North Carolina.

Figure 58: US Hwy 64 and adjacent canal at Milltail Rd, Alligator River National Wildlife Refuge, North Carolina.

Figure 59: US Hwy 64 and adjacent canal, just west of the junction with US Hwy 264, Alligator River National Wildlife Refuge, North Carolina.

Figure 60: East bank Lindsay C. Warren Bridge across Alligator River, Alligator River NWR, North Carolina.

8.2. US Hwy 264 near Alligator River National Wildlife Refuge

From the junction with US Hwy 64 to at least south of Borrow Pit Rd., or potentially much further south)

- This road section is mostly forest, with agricultural or early succession fields nearby.
- Given the relatively low traffic volume in this area (550-1,100 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- This road section is close to the Milltail area which is an important birth location for red wolves. To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles can be implemented (Figure 61, 62). For the red wolves in the Milltail area, the fence should be extended to south of Borrow Pit Rd. For red wolf conservation in general, the entire length of US Hwy 264 should be fenced.
- Potentially include the landfill and the gun club in the fenced road corridor; i.e., make these areas inaccessible to red wolves (Figure 63). This will “cost” habitat, but it will also reduce human-wildlife conflict and habituation of red wolves which can be hazardous to them in the long-term and at other locations after dispersal. Naturally, this will also result in habitat loss for other large mammal species for which the fence is a barrier. Alternatively, smaller areas can be fenced around the two facilities, but then wildlife guards and associated electrified barriers would have to be implemented at the access points.
- Minimize the number of access roads to the surrounding areas, including the refuge. For the refigure there is currently already one entrance in this area at Borrow Pit Rd.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- Specifically for red wolves, crossing structures can be considered for daily movements, but these crossing structures would not have the objective of facilitating dispersal of red wolves towards the east as there is little habitat present and there is no historic evidence of red wolf birth locations east of US Hwy 264.
- Existing structures in the area are typically for canals (Figure 64). These structures have no or almost no dry space, and have very low clearance. These structures are not suitable for large terrestrial mammals.

Figure 61: US Hwy 264, near the junction with US Hwy 64, Alligator River NWR, North Carolina.

Figure 62: US Hwy 264, near Cub Rd., Alligator River NWR, North Carolina.

Figure 63: US Hwy 264, suggested wildlife fence around the landfill and gun club, Alligator River NWR, North Carolina.

Figure 64: US Hwy 264, bridge at Point Peter Rd, Alligator River NWR, North Carolina.

8.3. US Hwy 264 Shaol River

- This area is mostly a wetland. It is possible that the Long Shaol River or Stomper Rd. guides the red wolves to US Hwy 264 (Figure 65, 66, 67).
- Given the relatively low traffic volume in this area (400-550 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length (both sides of the highway) is recommended.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- The existing bridge may be made suitable with pathways for large terrestrial mammal species.
- Crossing structures can be considered for daily movements for red wolves, and for other species, but crossing structures would not have the objective of facilitating dispersal of red wolves towards the south for this road section as there is little habitat present and there is no historic evidence of red wolf birth locations south of US Hwy 264.

Figure 65: US Hwy 264, at Long Shaol River, Alligator River National Wildlife Refuge, North Carolina.

Figure 66: US Hwy 264, at Long Shaol River, Alligator River National Wildlife Refuge, North Carolina.

Figure 67: US Hwy 264, at Long Shaol River, Alligator River National Wildlife Refuge, North Carolina.

8.4. US Hwy 264, north of Engelhard

- This area is mostly agricultural (Figure 68, 69).
- Given the relatively low traffic volume in this area (400 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length (both sides of the highway) is recommended.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- Crossing structures can be considered for daily movements for red wolves, and for other species, but crossing structures would not have the objective of facilitating dispersal of red wolves towards the east as there is little habitat present and there is no historic evidence of red wolf birth locations east of US Hwy 264.

Figure 68: US Hwy 264, US Hwy 264, north of Engelhard at junction with Smith Ave, North Carolina.

Figure 69: US Hwy 264, US Hwy 264, north of Engelhard at junction with Smith Ave, North Carolina.

8.5. Hwy 94, near Frying Pan Rd.

- This area is mostly agricultural with some woodland (Figure 70, 71).
- Given the relatively low traffic volume in this area (1,200 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length (both sides of the highway) is recommended.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- Crossing structures can be considered for daily movements for red wolves, and for other species. Here, crossing structures would also have the objective of facilitating dispersal of red wolves towards the east and west, as there is substantial habitat present and there is historic evidence of red wolf birth locations west and east of Hwy 94. While a wildlife fence without suitable crossing structures for the target species is almost never advisable, it would definitely be damaging to red wolf conservation to have a fence only in this area.
- The bridge across Riders Creek (Figure 72) is currently not suitable for large terrestrial mammals.

Figure 70: Hwy 94, south of junction with Frying Pan Rd., North Carolina.

Figure 71: Hwy 94, north of junction with Frying Pan Rd., North Carolina.

Figure 72: Hwy 94, Bridge across Riders Creek, north of junction with Frying Pan Rd., North Carolina.

8.6. Frying Pan Rd.

- This area is mostly agricultural with some woodland (Figure 73, 74).
- Given the very low traffic volume in this area (60 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length (both sides of the highway) is recommended.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- Crossing structures can be considered for daily movements for red wolves, and for other species. Here, crossing structures would also have the objective of facilitating dispersal of red wolves towards the north and south, as there is substantial habitat present and there is historic evidence of red wolf birth locations north of Frying Pan Rd. While a wildlife fence without suitable crossing structures for the target species is almost never advisable, it would definitely be damaging to red wolf conservation to have a fence only in this area.

Figure 73: Frying Pan Rd., North Carolina.

Figure 74: Frying Pan Rd., North Carolina.

8.7. Hwy 94, north of Fairfield

- This area is a mixture of agriculture, forest and wetlands (Figure 75, 76, 77, 78, 79).
- Given the low traffic volume on this road (400-450 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length (both sides of the highway) is recommended.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- Crossing structures can be considered for daily movements for red wolves, and for other species. Here, crossing structures would also have the objective of facilitating dispersal of red wolves towards the east and west, as there is substantial habitat present and there is historic evidence of red wolf birth locations east and west of Hwy 94. While a wildlife fence without suitable crossing structures for the target species is almost never advisable, it would definitely be damaging to red wolf conservation to have a fence only in this area.
- The bridge across the intracoastal waterway is not suited for red wolves as the habitat is wetlands (Figure 77, 78). Only if the approaches would extend into the dry areas, and if there would be a proper height, could the structure be made functional for red wolves.

Figure 75: Hwy 94, north of Fairfield, North Carolina.

Figure 76: Canal adjacent to Hwy 94, north of Fairfield, North Carolina.

Figure 77: Hwy 94, bridge across Intracoastal Waterway, north of Fairfield, North Carolina.

Figure 78: Wetlands adjacent to Hwy 94, bridge across Intracoastal Waterway, north of Fairfield, North Carolina.

Figure 79: Hwy 94, south of Gum Neck, North Carolina.

8.8. Beech Ridge Rd., north of Belhaven

- This area is a mixture of agriculture with dispersed houses, and forest (Figure 80, 81, 82).
- Given the low traffic volume on this road (910 AADT), general road reconstruction because of human safety or traffic congestion is unlikely. Mitigation measures will likely have to be a stand-alone project.
- To reduce the likelihood of direct red wolf mortality, a 10 ft (3 m) tall chain-link wildlife fence with metal poles along the entire length (both sides of the highway) is recommended.
- In general, if a wildlife fence is implemented, it should be accompanied by wildlife crossing structures.
- Crossing structures can be considered for daily movements for red wolves, and for other species. Here, crossing structures would not have the objective of facilitating dispersal of red wolves towards the south, as there is limited habitat present to the south and there is no historic evidence of red wolf birth locations south of Beech Ridge Rd.

Figure 80: Beech Ridge Rd, near Oak Ridge Lane, North of Belhaven, North Carolina.

Figure 81: Beech Ridge Rd, near Oak Ridge Lane, North of Belhaven, North Carolina.

Figure 82: Beech Ridge Rd, near Oak Ridge Lane, North of Belhaven, North Carolina.

9. CONCLUSION

9.1. General approach

Assuming existing roads will not be removed or moved, and assuming there will not be any seasonal or night-time closure, avoidance of the impacts of roads and traffic on red wolves along paved highways and other system roads is not realistic. This means that the impacts will remain, and that mitigation of these impacts needs to be explored. The only mitigation package that achieves both a substantial reduction in collisions and that allows for safe crossing opportunities, is wildlife fences in combination with wildlife crossing structures. In addition to mitigation, compensation is also an option. Additional habitat could be made available (e.g., increase the area of the ENC RWP). However, it seems that the conditions within the current ENC RWP need to improve before compensation through additional habitat can be expected to make a positive impact on population size and viability.

9.2. US Hwy 64 vs. other roads in the area

For many years already, plans have been prepared to reconstruct US Hwy 64 between Columbia and the Atlantic coast. When this reconstruction is initiated, it would likely make the current 2-lane highway into a divided 4-lane highway, similar to west of Columbia. Wildlife fences and wildlife crossing structures are likely to be an integral part of this highway reconstruction project. There are several considerations for this scenario:

- Combining the construction of wildlife fences and wildlife crossing structures with an overall reconstruction of a highway is usually less costly and more efficient than implementing the mitigation measures as a stand-alone project. However, the downside is that general reconstruction projects are usually initiated because of safety concerns and traffic congestion rather than the ecological impacts of a highway. This means that the reconstruction and associated mitigation measures may not be initiated for a long time, or they may not be initiated at all. During this “waiting time” impacts continue for wildlife. In this case, the establishment of a viable red wolf population is likely to continue to be problematic during this “waiting time” and this “waiting time” may never end.
- To reduce red wolf road mortality, mitigating roads with a traffic volume between 2,501-5,000 vehicles per day is more “efficient” than mitigating along roads with a lower or higher traffic volume (Chapter 8). This predominantly relates to US Hwy 64 and provides a rationale for implementing mitigation measures along this road first before other roads are mitigated. Mitigating US Hwy 64 would address the “most” red wolf road mortalities for the shortest length of mitigated road.
- However, the road mortality of red wolves is not restricted to US Hwy 64. While reconstruction of US Hwy 64 and associated mitigation measures is likely to reduce road mortality for red wolves, substantial road mortality would remain, especially along US Hwy 264 and Hwy 94 (provided that if the red wolf population increases again in these areas). If all system roads in the ENC RWP area with a traffic volume between 2,501-500 vehicles per day would be mitigated, “only” 20 out of the 78

(25.64%) historic red wolf mortalities on the system roads would be addressed (Chapter 4). Specifically for US Hwy 64, regardless of where along this highway, "only" 19 out of 78 (24.36%) red wolf mortalities on the system roads would be addressed.
- Based on historic data, breeding red wolves are in close proximity along US Hwy 64, particularly around the Miltail area (Chapter 5). Therefore, mitigation measures along US Hwy 64 would reduce the risk of road mortality for breeding pairs and their offspring. However, the same breeding pairs and their offspring would still be exposed to the dangers of US Hwy 264, especially near the landfill area. In addition, other roads, including very low volume roads, are in close proximity to other breeding pairs and their offspring (Chapter 5)
- While it is considered good practice to combine wildlife fences with wildlife crossing structures, the number of birth locations north of US Hwy 64 is relatively low (Chapter 5). In this context, crossing structures along US Hwy 64 would not necessarily allow for better access to substantial areas with good habitat quality where breeding is known to have occurred in the past. Instead, crossing structures along Hwy 94 would allow for better or safer access to substantial areas with good habitat quality on both sides of the road where breeding is known to have occurred in the past (Chapter 5).
- Potential future mitigation for red wolves along US Hwy 264 and Hwy 94 is likely to be a stand-alone project as the traffic volume is low and a general road reconstruction because of human safety or congestion of these highways is unlikely in the foreseeable future.

In conclusion, when US highway 64 is upgraded and mitigated, the benefits for red wolf conservation are primarily through reduced direct road mortality (24.36% reduction in overall road mortality on system roads if the potential future measures along US Hwy 64 are 100% effective in eliminating road mortality) rather than safer access to proven breeding habitat further north. Substantial road mortality would remain along US Hwy 264 and highway 94. Mitigation measures along the eastern sections of US Hwy 264 would also benefit red wolf conservation primarily through reduced direct road mortality rather than safe passage to proven breeding habitat further east and south. However, mitigation measures south of Lake Mattamuskeet and further west, and mitigation measures along Hwy 94 would likely both substantially reduce road mortality for red wolves, and also provide for safe passage that would connect large tracks of suitable breeding habitat. In contrast to US Hwy 64, mitigation measures along US Hwy 264 (21 out of the 78 (26.92%) red wolf mortalities on the system roads) and Hwy 94 (15 out of the 78 (19.23%) red wolf mortalities on the system roads) would likely require stand-alone projects that are primarily rooted in conservation.

9.3. Wildlife fences vs. wildlife fences in combination with wildlife crossing structures

While it is considered bad practice to only implement wildlife fences and not combine them with safe crossing opportunities for wildlife, immediate wildlife fencing along US Hwy 64 and parts of US Hwy 264 may be what is needed for the immediate survival of the few remaining red wolves (Jaeger & Fahrig 2004). However, if wildlife crossing structures are not an integral part of the mitigation measures, other species may suffer, and for the long-term conservation of the red wolf, habitat connectivity is essential, especially along US Hwy 94 as there are large areas with suitable habitat and there is historic evidence of birth locations on both sides of the highway. Furthermore, if wildlife crossing structures are not implemented at the same time as wildlife fences, the wildlife crossing structures may never be implemented, despite good intentions.

9.4. Spatial scale of mitigation measures

While it is useful to identify and prioritize road sections in need of mitigation based on historic and current collision hotspots and connectivity needs, it is important to realize that:

- For wildlife fences to substantially reduce direct road mortality of red wolves, long road sections need to be mitigated; the length of a collision hot spot plus an additional 2.5-3.5 miles on either side of the hotspot (i.e., at least 5-7 miles of road length in total). A more spatially precise identification and prioritization process with short, mitigated road lengths (e.g., a few hundred yards or up to a few miles) is unlikely to reduce road mortality overall, nor is road mortality likely to be reduced on the long term. Short sections of fence will likely move road mortality to adjacent road sections rather than really reduce overall road mortality (Huijser & Begley 2022), and when other areas are also occupied by red wolves in the future, the original short sections of fence will not protect the animals in these other areas.
- For the location of wildlife mitigation measures it is good practice to base this on existing knowledge of where the target species are willing to come close to the highway or where they have been observed crossing that highway. However, similar to the previous point, this is highly dependent on where red wolves were during the period when the location and movement data were collected. Therefore, it is better to base the location of wildlife mitigation measures on general ecological principles of where red wolves have been observed close to the highway or where they have been observed crossing the highway. In other words, higher and drier habitat, especially where unpaved roads (or trails) approach the main highway. Nonetheless, if wildlife crossing structures are constructed, hydrology and soil stability, as well as land ownership may all influence the location of the structures. If wildlife crossing structures are constructed in association with general road reconstruction, the immediate surroundings (vegetation, canals, unpaved road access points) may all change. This would then be an opportunity to rethink the configuration of the roads on the refuge and where the fewer access points to the main highway are, especially in combination with designing the approaches for wildlife of the wildlife crossing structures.

9.5. Costs and benefits

Wildlife fences, wildlife crossing structures and associated measures may be considered costly, especially if they are initiated as a stand-alone project rather than as part of a general road reconstruction project. However, there are also costs to doing nothing. Historically we have mostly paid attention to vehicle repair costs and the costs associated with human injuries and human fatalities when we hit large wild mammals (e.g., Huijser et al. 2009c). It is relatively new to also pay attention to economic parameters associated with wildlife conservation. For large mammals that are endangered and also considered charismatic by the public, an individual animal may be valued at several tens of thousands up to several million dollars (USFWS 1994, USFWS 2000, Duffield et al. 2006, Duffield & Neher 2019, Huijser et al. 2022b). The passive use value of red wolves in and around Alligator River National Wildlife Refuge may be comparable to that of the value of gray wolves in Yellowstone National Park where they were valued at about US$2 million per individual (USFWS 1994, Duffield & Neher 2019). In this context, it may not be "cost prohibitive" to implement mitigation measures for red wolves. Even stand-alone mitigation projects for species similar to the red wolf may be considered defensible on economic arguments alone (Huijser et al. 2022b, Adams et al. 2023).

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APPENDIX: EXPLORATION OF RED WOLF MORTALITY DATA

Introduction

This appendix contains an exploration of the mortality records of wild red wolves from the Eastern North Carolina Red Wolf Population (ENC RWP). The area includes federal, state, and private lands in Beaufort, Dare, Hyde, Tyrrell, and Washington Counties, on the Albemarle Peninsula of North Carolina. This chapter is focused on exploring the relative importance of direct road mortality compared to other causes of mortality, particularly unnatural causes of mortality.

Methods

Red wolf mortality data were obtained from USFWS (Arthur Beyer, USFWS). The oldest mortality record in this database was from 29 April 1987, and the most recent mortality record was from 27 June 2022. The researchers selected records for red wolves from the ENC RWP that died in the wild. Thus, red wolves that died in captivity were excluded. However, red wolves that died in traps in the wild, legal or illegal, were included.

There were two mortality codes in the database:

- SUSP: Mortality as assessed in field.
- OFF: Result of official necropsy. However, not all carcasses were sent to the lab for a formal necropsy.

The researchers combined these two parameters into one mortality parameter according to the following protocol:

1. If OFF was populated, then this was the mortality code used for this report.
2. If OFF was not populated, then the code for SUSP was used for this report.

The new "combined" mortality parameter was analyzed for:

- Mortality numbers by mortality code (all mortality codes).
- Mortality numbers by month.
- Absolute mortality in relation to population size.
- Relative mortality in relation to population size.
- Spatial analysis to identify roadkill hotspots.

Results

Mortality numbers

The total number of reported and selected red wolf mortalities between 29 April 1987 and 27 June 2022 was 471. Of all reported and selected mortalities, gunshot (25.90%) and vehicle strike (19.96%) were by far the most frequently occurring known causes of death (Table 5).

Table 5: The frequency of different sources of mortality for red wolves (1987-2022).

Mortality Code	Mortalities (N)	Mortalities (%)
GUNSHOT	122	25.90
UNKNOWN	94	19.96
VEHICLE	91	19.32
INTRASPECIFIC	25	5.31
MANGE	17	3.61
PRIVATE TRAP	17	3.61
HEALTH	14	2.97
POISON	13	2.76
TRAP RELATED	13	2.76
FOUL PLAY	12	2.55
MANAGEMENT	11	2.34
HANDLING	9	1.91
NATURAL	9	1.91
EUTHANIZED	8	1.70
HEARTWORM	5	1.06
DROWNED	4	0.85
TRAUMA	2	0.42
AGE-RELATED	1	0.21
BLUNT FORCE TRAUMA	1	0.21
FIRE	1	0.21
IMPACTED COLON	1	0.21
UTERINE TORSION	1	0.21
Total	471	100.00

Excluding 1987 and 2022, which were not full years in the mortality database, the average percentage of gunshot mortalities per year out of the total reported mortalities was 23.96% (SD = 21.42). The average percentage of vehicle strikes per year out of the total reported mortalities was 22.67% (SD = 17.31).

Mortality by month

Excluding 1987 and 2022, which were not full years in the mortality database, the frequency of gunshot mortalities was highest from October through December (Figure 83). There was no clear seasonal pattern for mortality because of vehicle strikes or the combined other causes of mortality.

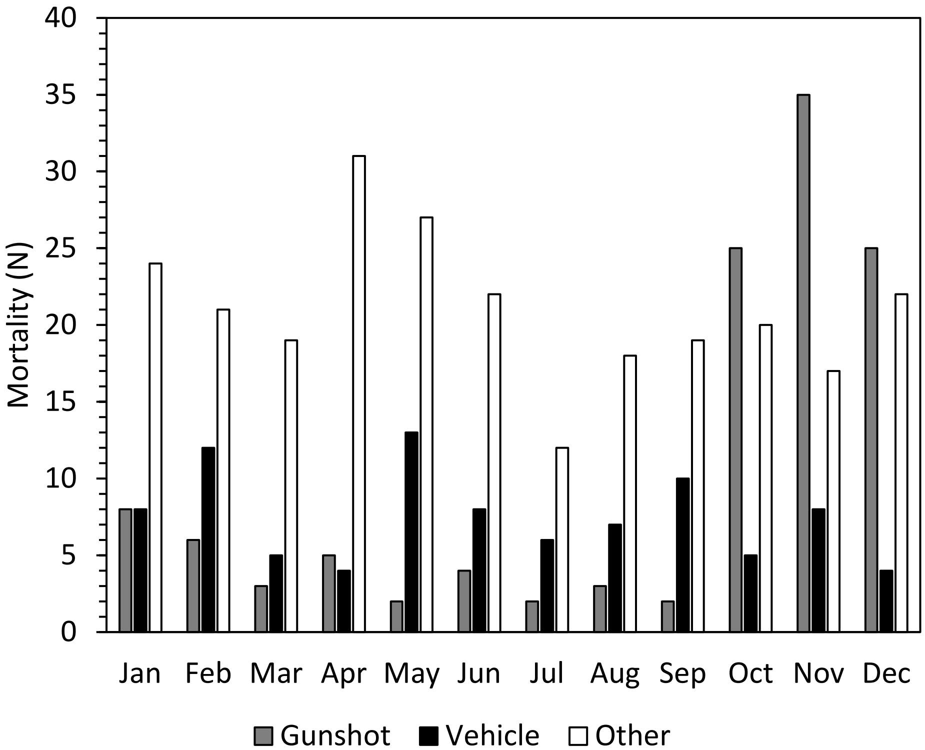

Figure 83: Red wolf mortality (1988 through 2021, N_{total}=462) by month because of gunshots, vehicle strikes, and other causes.

Absolute mortality in relation to population size

The red wolf population size of the ENC RWP at the end of each calendar year was estimated by USFWS (2022b). For some years there was not a single number but a range (minimum-maximum) for the estimated population size. When only a range was available, the average of the minimum and maximum population size estimate was used. In general, the red wolf population size increased between 1987 and 2000, remained relatively stable between 2001 and 2014 (81-110 individuals), and severely declined afterwards (Figure 84). While the population size was very low between 2019 and 2022, it had stabilized around 18-20 individuals (Figure 85). Greater population size was generally associated with higher overall absolute mortality (Figure 85). Absolute mortality because of gunshots, vehicle strikes, and "other" causes of mortality were all positively correlated with increasing population size (Figure 85, Table 6). For every additional red wolf in the population, 0.033 more red wolves were killed by vehicles (Figure 85, Table 6).

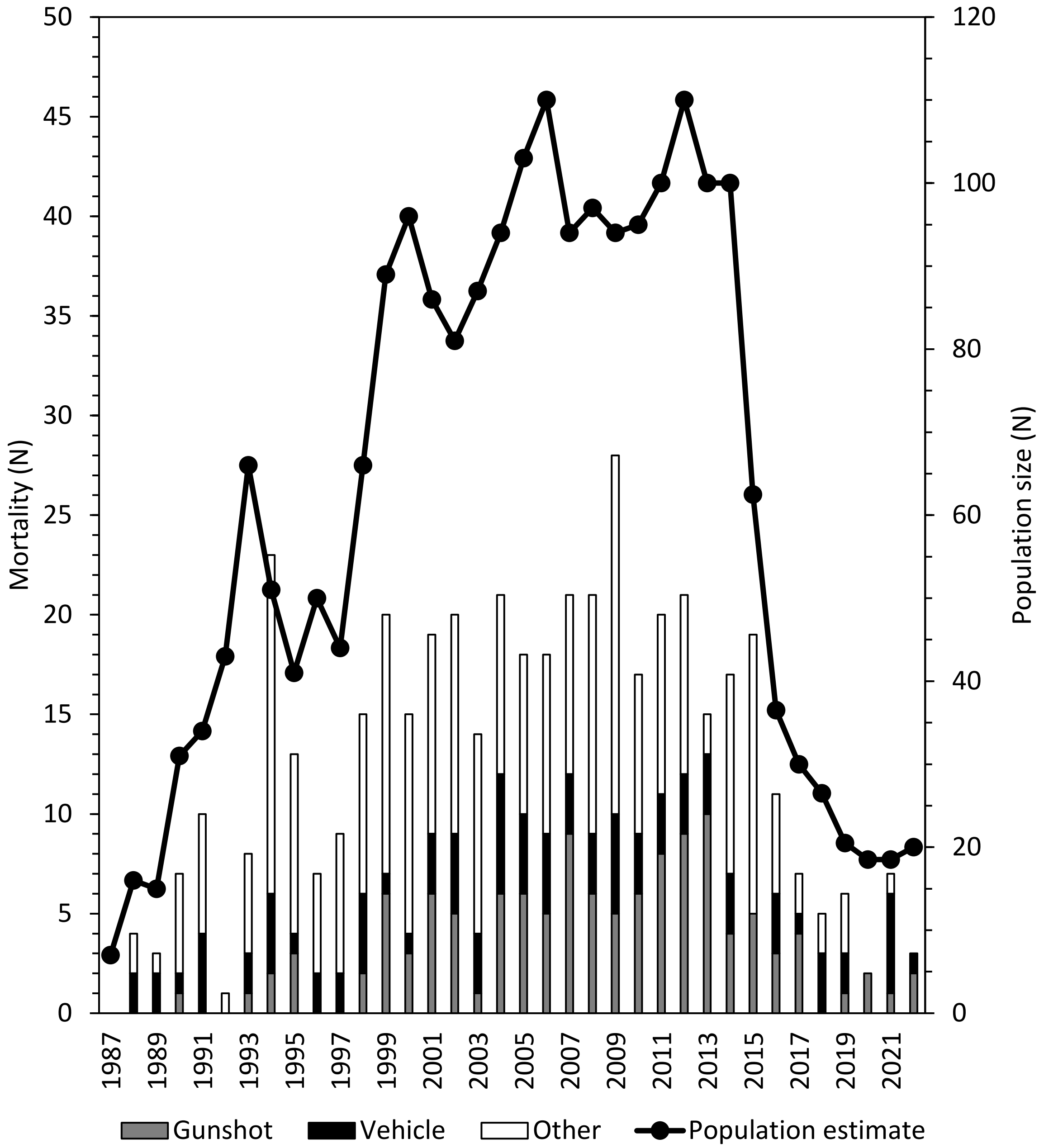

Figure 84: Annual mortality because of gunshots, vehicle strikes, and other causes between 1987 and 2022 (bars in the graph) and the estimated population size for each year (end of year) for the red wolf (line in graph).

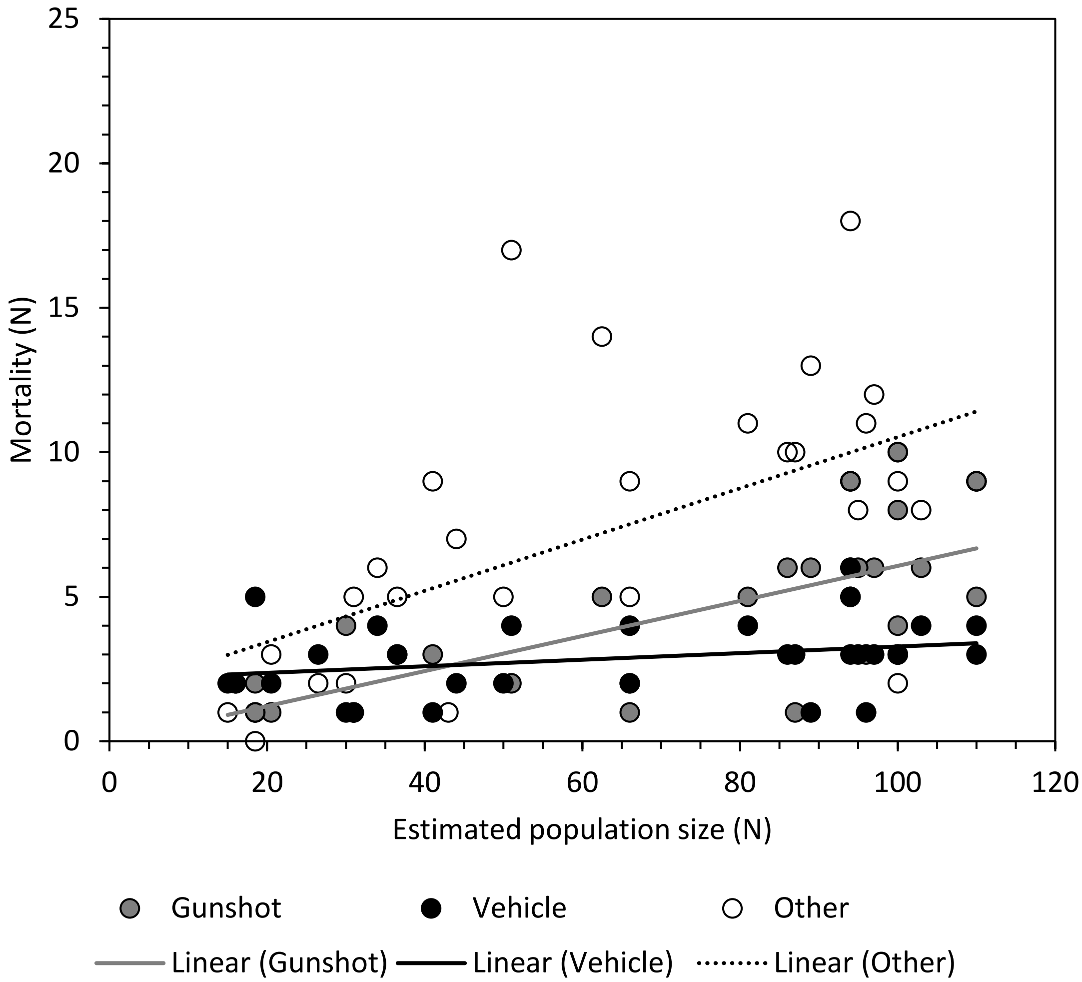

Figure 85: Absolute mortality (N) because of gunshots, vehicle strikes and other causes in relation to the population size of the red wolf. If a regression line is shown for a response variable, the relationship is significant (P≤0.05) (see Table 6).

Table 6: Output of the linear regression analyses of absolute mortality dependent on population size (Figure 85). The years 1987 and 2022 were excluded from the regression analyses as they were not full calendar years and different sources of mortality may be unequally distributed throughout the year.

Parameter	**Gunshot**	**Vehicle**	**Other**
R^2	0.4938	0.2610	0.1853
Slope	0.0607	0.0348	0.0504
P	<0.0001	0.0033	0.0110

Relative mortality in relation to population size

Excluding 1987 and 2022, which were not full years in the mortality database, the average percentage of gunshot mortalities per year out of the estimated population size was 4.95% (SD = 3.58). The average percentage of vehicle strikes per year out of the estimated population size was 5.38% (SD = 5.21). Gunshots, vehicle strikes, or other mortality causes expressed as a percentage of the population size did not significantly increase or decrease with increasing population size ($P>0.05$) (Figure 86, Table 7).

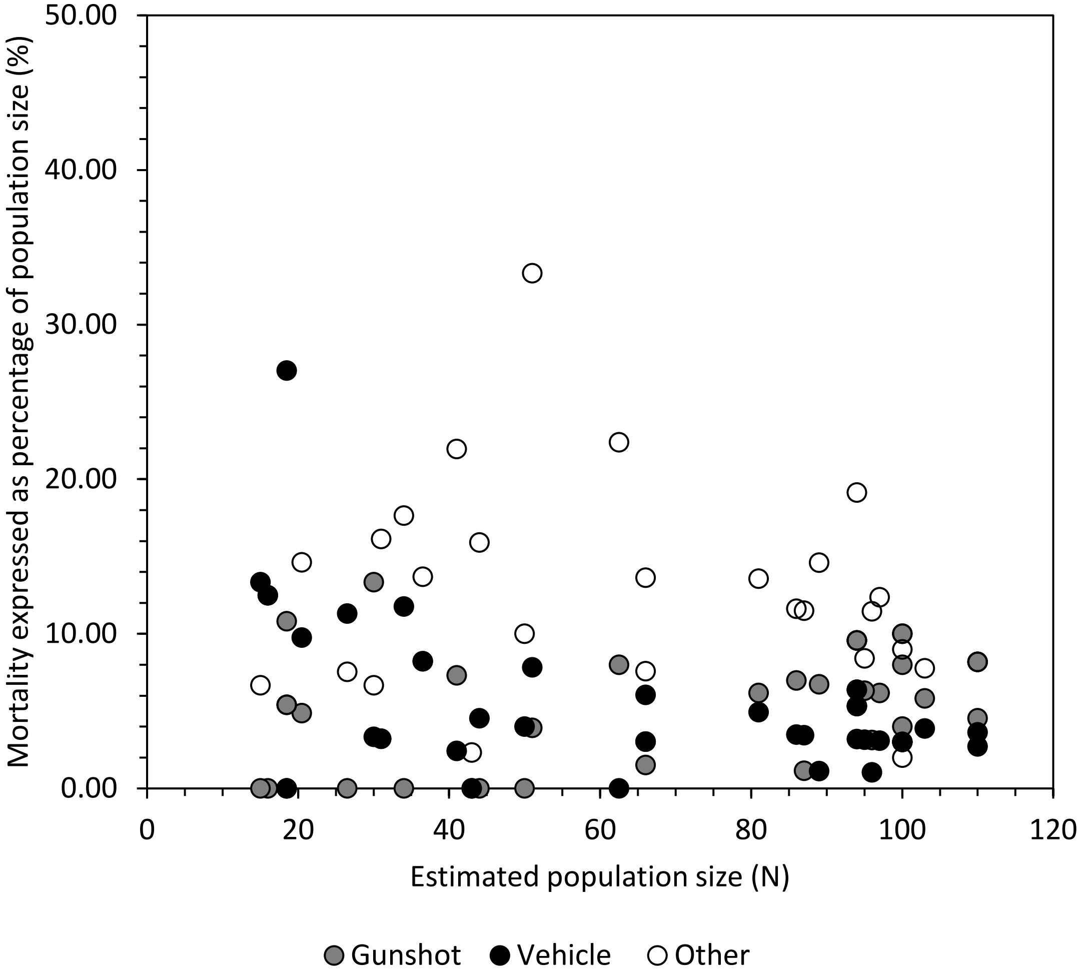

Figure 86: Mortality because of gunshots, vehicle strikes, and other causes expressed as a percentage of the total population size, in relation to the population size of the red wolf. If a regression line is shown for a response variable, the relationship is significant (P≤0.05) (see Table 7).

Table 7: Output of the linear regression analyses of mortality expressed as a percentage of total population size dependent on population size (Figure 86). The years 1987 and 2022 were excluded from the regression analyses as they were not full calendar years and different sources of mortality may be unequally distributed throughout the year.

Parameter	Gunshot	Vehicle	Other
R^2	0.0802	0.0339	0.0127
Slope	0.0310	-0.0252	-0.0209
P	0.1046	0.2972	0.5256

Discussion

Mortality numbers
Of all reported mortalities, gunshot (25.90%) and vehicle strike (19.96%) were the most frequently occurring known causes of death. Both causes of mortality are unnatural and can be considered problematic for a threatened species (combined mortality is 45.86% of reported mortality), especially one that has a critically low population size and a high risk of extirpation in the NC NEP.

Mortality by month
There was no clear seasonal pattern for mortality because of vehicle strikes, but gunshot mortalities were most numerous during deer hunting season.

Absolute mortality in relation to population size
Absolute mortality was positively correlated with increasing population size for gunshots, vehicle strikes, and other causes of mortality. Interestingly, gunshot mortalities increased by about twice the rate compared to mortality because of vehicle strikes with increasing population size. However, this is based on correlation. There may well be confounding variables for the increase in gunshot mortality in relation to population size. Examples of such potentially confounding variables may be changes in public attitude towards red wolves, the level of law enforcement, and an increase in coyotes and associated hunting of that species (Pers. com. Joe Madison and Art Beyer, Red Wolf Recovery Program).

Relative mortality in relation to population size
The average percentage of gunshot mortalities per year out of the estimated population size was 4.95% (SD = 3.58). The average percentage of vehicle strikes per year out of the estimated population size was 5.38% (SD = 5.21).