ESTIMATION OF DEEPWATER HORIZON OIL SPILL EFFECTS ON POPULATION DYNAMICS OF THE LOGGERHEAD SEA TURTLE (*CARETTA CARETTA*)

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Estimation of Deepwater Horizon Oil Spill Effects on Population Dynamics of the Loggerhead Sea Turtle (*Caretta caretta*)

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Deepwater Horizon (DWH) was the largest offshore oil spill in US history. The result was approximately 3.19 million barrels of oil being released into the ocean. *Deepwater Horizon* significantly affected the Gulf of Mexico and surrounding beaches, including threatened and endangered marine life such as the loggerhead sea turtle. Hence, we conducted a thorough literature review to obtain the demographic data and developed a stage-structured stochastic population dynamics model using STELLA® 7.0.1 for loggerhead sea turtles. We modeled three conservation scenarios along with a baseline scenario. Then we subjected the conservation scenarios to added oil mortality. We then used the model to quantify the potential effects of oil spills on the population of loggerhead sea turtles for the next decade. The results of the baseline model without oil effects show a decrease in the adult population from 119 in 1987 to 13 in 2026, implying the possibility of the population's extinction without any conservation efforts. All three conservation scenarios without oil effects show an increase over 40 years. Conservation scenarios after added linearly decreasing oil mortality from 2010 to 2019 all decreased about 79% in 2026 at the end of our 40-year simulation. Continued conservation efforts and assessments of loggerheads will ensure population numbers continue to recover following DWH.

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NOMENCLATURE

DWH	Deepwater Horizon
ESA	Endangered Species Act
IAC	Inter-American Convention
IUCN	International Union for Conservation of Nature
LCI	Little Cumberland Island
LHST	Loggerhead Sea Turtle
NOAA	National Oceanic and Atmospheric Administration

CHAPTER I

INTRODUCTION

The Gulf of Mexico is recognized worldwide as a vast and productive body of water. The Gulf is largely surrounded by the North American continent. The states of Texas, Louisiana, Mississippi, Alabama, and Florida share coastline on the Gulf. Its coastal region contains half the coastal wetlands in the United States and is home to abundant wildlife resources ("The Gulf of Mexico Ecosystem, Watershed, and Economy", 2008). These resources are supported by rich natural habitats, including bays, estuaries, tidal flats, barrier islands, hard and soft wood forests, and mangrove swamps ("The Gulf of Mexico Ecosystem, Watershed, and Economy", 2008). The size of the basin is approximately 1.6 million km^2 and almost half of the basin is shallow continental shelf waters ("Gulf of Mexico", 2017). About two-thirds of the United States belongs to the watershed area of the Gulf of Mexico and it receives freshwater from 33 major river systems, and many small rivers, creeks, and streams ("Gulf of Mexico", 2017). The role of the Gulf of Mexico is robust. The Gulf has important ocean currents and supplies moisture for the North American monsoon. The Gulf is also home to some of the most spectacular wildlife in the world and is a prominent area for commercial and recreational fisheries. Many onshore refineries and offshore drilling platforms operate in the Gulf area. They produce about a quarter of the crude oil and almost one-third of the natural gas in the United States ("Gulf of Mexico", 2017). The Gulf region's ecological communities are essential to sustaining nationally vital economic and recreational industries.

The Gulf of Mexico has several environmental quality problems that have surfaced as a result of natural processes, anthropogenic effects, and a combination of the two. These problems range from erosion, to oil and hazardous material spills, to trash washing ashore. These problems not only affect the water quality and ecosystems close to shore, but they also have led to problems such as hypoxia, a "dead zone", caused by the physical structure of the water column and high nutrient loads from the outflows of the Mississippi and Atchafalaya Rivers, which enhances primary production and decreases oxygen levels for a prolonged period (Rabalais, 2002). An important anthropogenic event that has routinely affected the Gulf terribly is oil spills. As the demand for oil surges, companies push farther into the ocean in search of petroleum (Paquette, 2013). In 2010, a BP owned oil well burst, releasing millions of barrels of oil into the Gulf of Mexico. This incident is known as the *Deepwater Horizon* (DWH) oil spill. Vast areas of the Gulf of Mexico were contaminated with oil, including deep-ocean communities and over 1,600 kilometers of shoreline (Barron, 2011).

One such marine life that fell victim to this spill was the loggerhead sea turtle (*Caretta caretta)*, which was listed as "threatened" by Endangered Species Act (ESA). They face multiple direct and indirect impacts as a result of this oil spill event. All post-hatch life stages are vulnerable to oil effects due to certain aspects of their biology and behavior. Their lack of avoidance behavior, indiscriminate feeding in convergent zones, and large pre-dive inhalation (Milton et al., 2003) cause effects such as egg mortality and developmental defects, direct mortality due to oiling in hatchlings, juveniles and adults, and impacts to the skin, blood, salt glands, and digestive, and immune systems (Conant et al., 2009). According to Dr. Blair Witherington, the Gulf spill harmed young surface-pelagic turtles profoundly. Their smaller size leads to the susceptibility of being overwhelmed by a given amount of oil as well as underdeveloped metabolic machinery used to detoxify and cleanse contaminants from the body (Shigenaka, 2010).

The group Inter-American Convention (IAC) for the Protection and Conservation of Sea Turtles released a loggerhead status report in December 2016 drawing from existing (1) reviews, such as International Union for Conservation of Nature (IUCN) Red List assessments, the ESA status assessment, major regional status reviews, information provided in countries' annual reports, and information provided by members of the IAC Scientific Committee, and (2) data which had been gathered from a total of 34 nesting beaches among the nations, including United States, and eight of these sites have long-term data of 10 years or more (Chapman, 2016). Based on the report, there are a mean of 58,348 nests deposited each year from 2009-2015 across the participating nations, which equates to 42,693 adult females in the population (Chapman, 2016). The United States contains the majority of loggerhead nesting for the IAC region and the Northwest Atlantic regional population has an estimated number of females >40,000 and a stable loggerhead population (Chapman, 2016).

Even though the current loggerhead population is stable (Chapman, 2016) and the immediate studies following the spill seemed to find that the decline of the population of loggerhead sea turtle is not greatly accelerated by a single, localized oil spill (Leung, 2012), I hypothesize that the DWH oil spill could have long-term negative effects on the loggerhead population. Thus, I aimed to use population models to explore how the event of DWH oil spill affected the population dynamics for loggerhead sea turtles over the decade following the event.

CHAPTER II

METHODS

Focal Species

The loggerhead is a sub-tropical and temperate migratory species with a complex life history (Witzell, 2002). In the generally accepted life history model for loggerhead turtles, sexually mature animals of both sexes migrate from their foraging areas to mate in the vicinity of their natal beaches (Cejudo, 2013). Several studies of different sea turtle species have confirmed that after mating, males return to the foraging area (Arendt et al., 2012a; James et al., 2005a; Schofield et al., 2010a; Shaver et al., 2005; Van Dam et al., 2008) while females come ashore to lay eggs several times over the course of the nesting season (Cejudo, 2013). After incubation, hatchling turtles emerge from the nest and make their way to the sea (Cejudo, 2013). During the first few years of life, these small juvenile turtles are thought to occupy oceanic habitats and feed on pelagic organisms (Bolten, 2003; Musick and Limpus, 1997). When juvenile turtles reach larger sizes (46-64 cm, estimated for Western North Atlantic populations; Bjorndal et al., 2000), they typically move to coastal neritic habitats, often close to their natal beaches, and change their foraging behavior to feed on benthic fauna (Hopkins-Murphy et al., 2003). After reaching sexual maturity, turtles may change their neritic foraging grounds or continue using juvenile feeding areas (Limpus and Limpus, 2003). During non-nesting years, adult females from U.S. beaches are distributed in waters off the eastern U.S., The Bahamas, Greater Antilles, and Yucatán, and throughout the Gulf of Mexico (National Marine Fisheries Service and U.S. Fish and Wildlife Service, 2008). For loggerheads in the Northern Gulf, timing of peak post-nesting migration varies by individual and year…it is not yet known what drives this timing of migration, the timing of nesting activity may differ among years depending upon sea surface temperature (Hart, 2017). Along the east coast, Northern movements seemed to be associated with both increased sea surface temperature (>21°C) and increased primary productivity (Mansfield K.L, 2009).

Research Area

The loggerhead occurs throughout the temperate and tropical regions of the Atlantic, Pacific, and Indian Oceans (National Marine Fisheries Service and U.S. Fish and Wildlife Service, 2008). In the U.S., loggerheads nest from Texas to Virginia (National Marine Fisheries Service and U.S. Fish and Wildlife Service, 2008). The majority of nesting in the southeast U.S. currently occurs on over 2,400 km of beaches: North Carolina (531 km), South Carolina (303 km), Georgia (164 km), Florida (1,327 km), and Alabama (78 km) (National Marine Fisheries Service and U.S. Fish and Wildlife Service, 2008). Our research used data which was gathered by National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NMFS-NE-207 that possessed counts of loggerhead sea turtle (*Caretta caretta*) nests at index beaches in the Western North Atlantic from 1996-2005 (NMFS-NE-207, 2008). Index beaches are Northern (NC, SC, GA), Peninsular Florida, Dry Tortugas (Florida), and Northern Gulf (FL, AL) (Fig. 1; Assessment Update for the Kemp's Ridley and Loggerhead Sea Turtle Populations in the Western North Atlantic, 2000; see Appendix for copyright information).

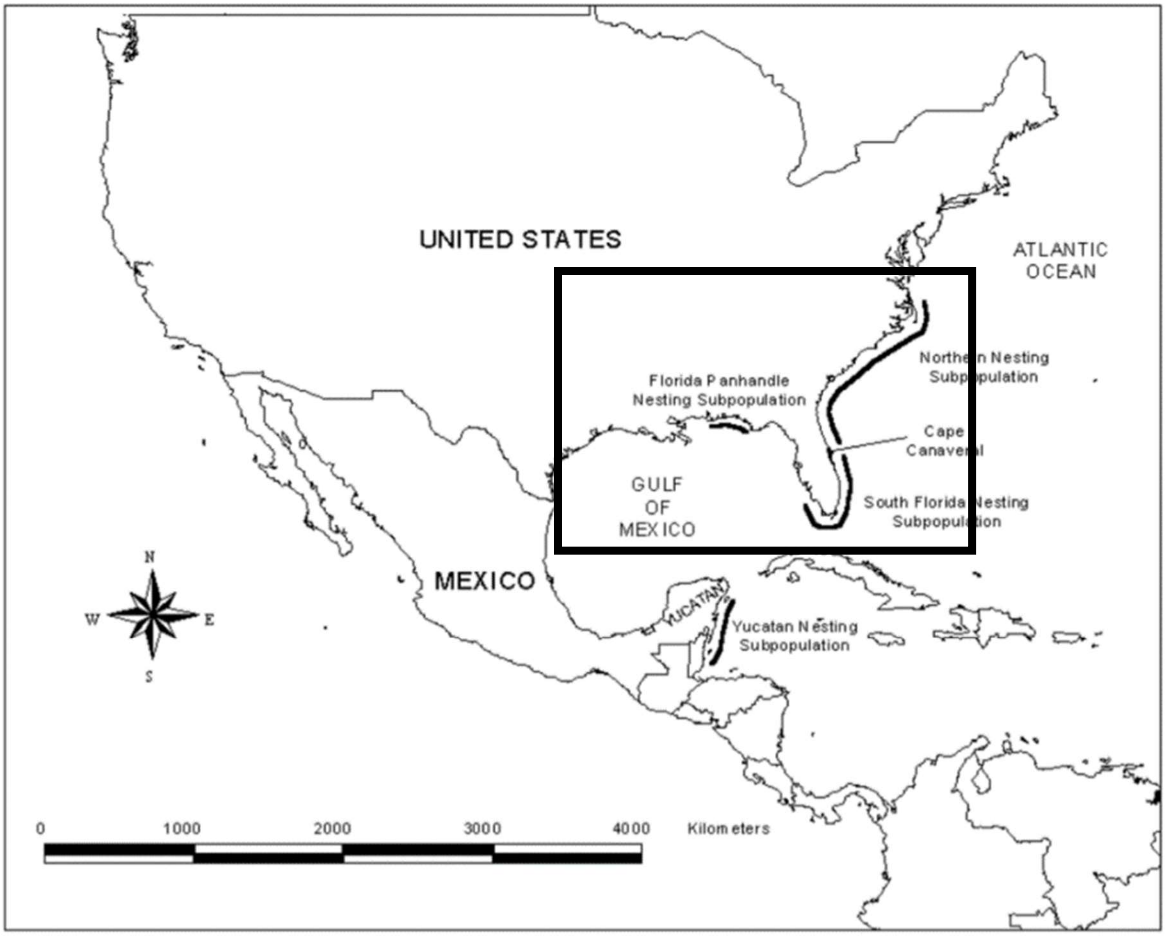

Figure 1. Loggerhead nesting areas, Western North Atlantic.

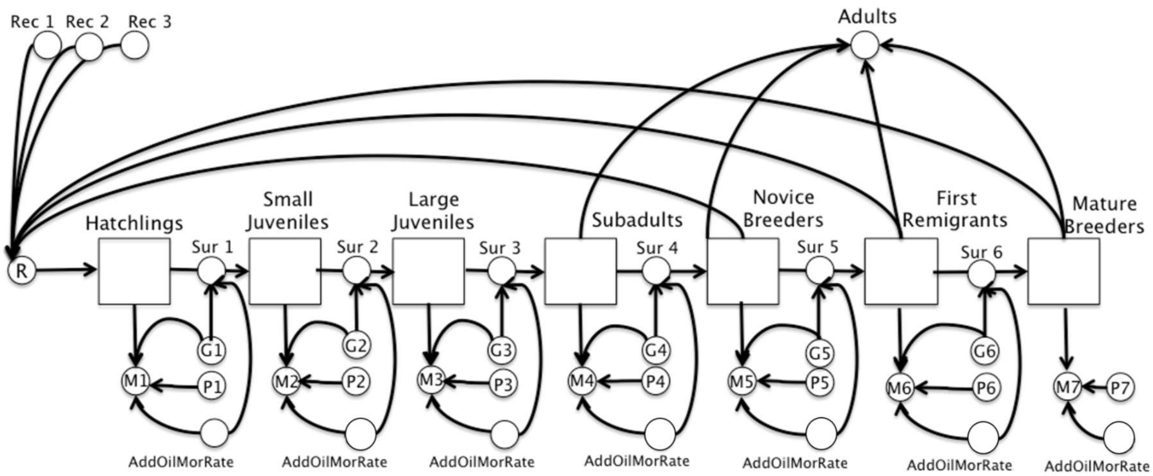

Figure 2. Conceptual model representing effects of Deepwater Horizon oil spill on population dynamics of loggerhead sea turtle over time. Boxes represent state variables, large arrows represent material transfers, small arrows represent information transfers, circles represent driving variables (AddOilMorRate) or constants (Rec, Remigration Year, G, P, Adults).

Model development

The model, which represented the Western North Atlantic loggerhead sea turtle population dynamics over the course of three decades, consisted of a baseline scenario that excludes any influence by oil exposure on mortality and three conservation scenarios each represented both without added oil mortality and with added oil mortality: (1) conservation scenario 1 represented the population if survivorship in immature (eggs and hatchlings) increased to 0.80, (2) conservation scenario 2 represented the population if survivorship in large juveniles/subadults, and adults increased to 0.80 and 0.85 respectively, (3) and conservation scenario 3 represented the population if survivorship in first-year (included in hatchlings), large juveniles/subadults, and adults increased to 0.33735, 0.80, and 0.85 respectively (Fig. 2). The model was formulated as a stochastic discrete-time compartment model based on the different equations with a 1-year time step. Simulations were run using the modelling software STELLA® 7.0.1, developed with default parameters.

Loggerhead population life stages were divided into 7 categories, each of which with different survival rates: hatchlings, small juveniles, large juveniles, subadults, novice breeders, first remigrants, and mature breeders. Crouse et al. (1987) characterized these life stage divisions by Frazer (1983a) findings of loggerhead fecundity, survival, and growth rates.

Boxes represented state variables and were divided based on loggerhead life stages. Arrows (material transfers) portrayed individuals entering and leaving each stage in the form of recruitment (R) and survival (Sur1, Sur2, etc.) (1), as well as those exiting through mortality (Mor1, Mor2, etc.) (2). G1, G2, etc. represented the probability of surviving and growing to the next stage, whereas P1, P2, etc. represented the probability of surviving and remaining in the same stage class. "Adults" were the individuals in the last three stages combined. Each conservation scenario with added oil mortality had an additional parameter, called additional oil mortality rate (AddOilMorRate) (3). This rate of oil exposure was additive to mortality. We collected values for P and G parameters from Table 4 and Table 6 in Crouse et al. (1987).

$$\text{Sur} = \text{previous life stage} \times \text{G} \times (1 - \text{AddOilMorRate}) \qquad (1)$$

$$\text{Mor} = \text{life stage} \times (1 - \text{G} - \text{P}) \qquad (2)$$

$$\text{AddOilMorRate} = \text{LessOil} \times \text{Probability1} + \text{MediumOil} \times \text{Probability2} + \text{HeavyOil} \times (1 - \text{Probability1} - \text{Probability2}) \qquad (3)$$

We collected starting population numbers based on NOAA Technical Memorandum NMFS-NE-207 Table 3 counts of loggerhead sea turtle nests in the Western North Atlantic from 1996-2005. We assumed that nest counts are equivalent to the number of female individuals in the population. We summed and then averaged Table 3 nest values to find the average nest count over the 9 years in which nest counts were monitored in the area. The resulting value was then multiplied by stable age distribution (Table 1) producing the number of individuals in each respective life stage. The model ran for 40 years from 1987 to 2026 with a starting population of 47,723: 9,855 hatchlings, 31,962 small juveniles, 5,469 large juveniles, 315 subadults, 19 novice breeders, 14 first remigrants, and 86 mature breeders. We took recruitment values from Table 3 in Crouse et al, 1987 where novice breeders yield a fecundity, number of eggs/year, of 127, first remigrants a fecundity of 4 and mature breeders a fecundity of 80.

Table 1. Stable age distribution for the loggerhead population.

Stage Class	Stable Stage Distribution (percent)
1 (hatchlings)	20.65
2 (small juveniles)	66.975
3 (large juveniles)	11.46
4 (subadults)	0.66
5 (novice breeders)	0.04
6 (1st-yr remigrants)	0.03
7 (mature breeders)	0.18

We calculated the stochastic portion of the model using three levels of oil exposure, less, medium, and heavy. Using a probability function each level of oil exposure was assigned a random number between 0 and 1, when combined AddOilMorRate = 1. We took level of oil exposure values from Mitchelmore et al. (2017) where less oil = 0.208, medium oil = 0.279, and heavy oil = 0.374. Added oil mortality rate decreased linearly over a ten-year period based on Merv Fingas, "The Basics of Oil Spill Clean Up", Third Edition. We applied values for added mortality rates graphically with years (0-40) on the x-axis and AddOilMorRate on the y-axis (0-1). Added oil mortality rate was applied on the twenty-third year. The twenty-third year of simulation being 2010 at the occurrence of DWH oil spill.

CHAPTER III

RESULTS

The stage-structured stochastic population dynamics model we developed used yearly iterations to make population projections for loggerhead sea turtle (Crouse et al. 1987). For the baseline simulation we saw a decrease in individuals from 119 in 1987 to 13 in 2026. After modelling our 3 conservation scenarios without added oil mortality, the population increased in each scenario 993.14%, 1,244.61%, and 265.86% respectively. Conservation scenario 2, which focused on increasing survivorship in large juveniles/subadults and adults, showed the greatest increase in population numbers over the 40-year simulation at 1,244.61% (Fig. 3).

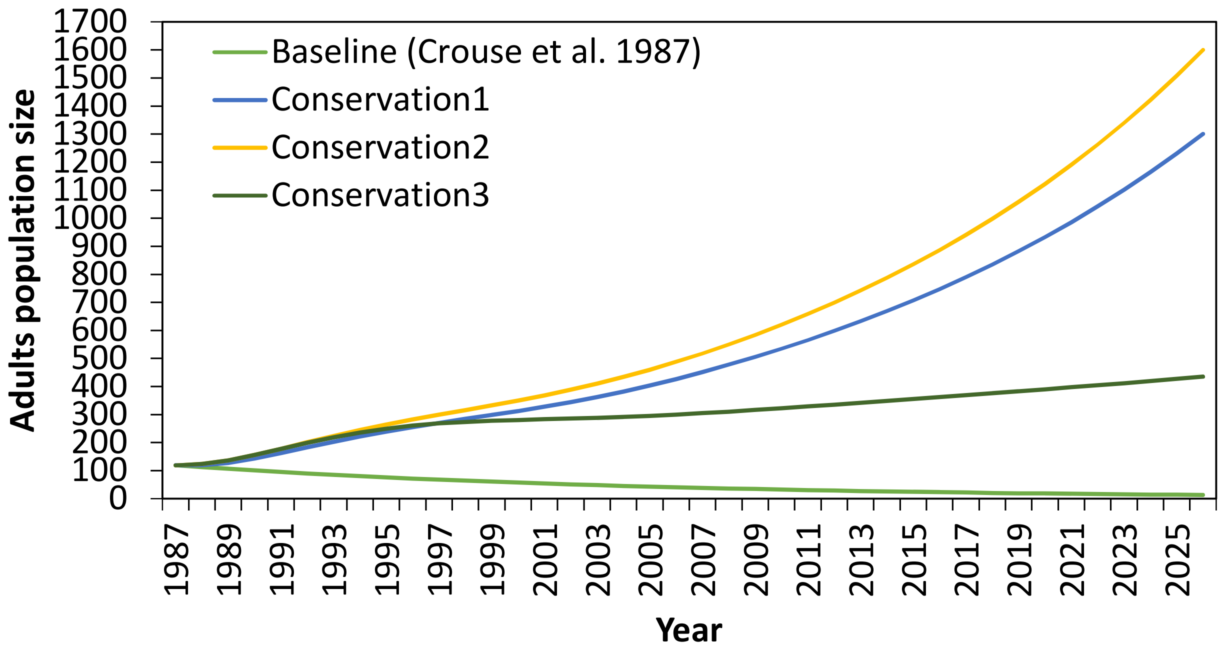

Figure 3. Graph of baseline scenario and conservation scenarios 1, 2, and 3 without added oil effects. Green line represents the baseline scenario. Blue line represents conservation scenario 1. Yellow line represents conservation scenario 2. Dark green line represents conservation scenario 3.

Conservation scenario 1 with added oil mortality effects showed a growth in the population until 2010 when oil mortality as a result of DWH oil spill caused a decrease in the population (Fig. 4). When we compared the effected population in 2026 at the end of the 40-year simulation at approximately 276 individuals to its respective population size without added oil mortality at approximately 1,301 individuals we found this comparison showed a population decrease of 78.7%. As our added oil mortality rate parameter decreased linearly over the 10-year period, we can see that the population slowly began to recover.

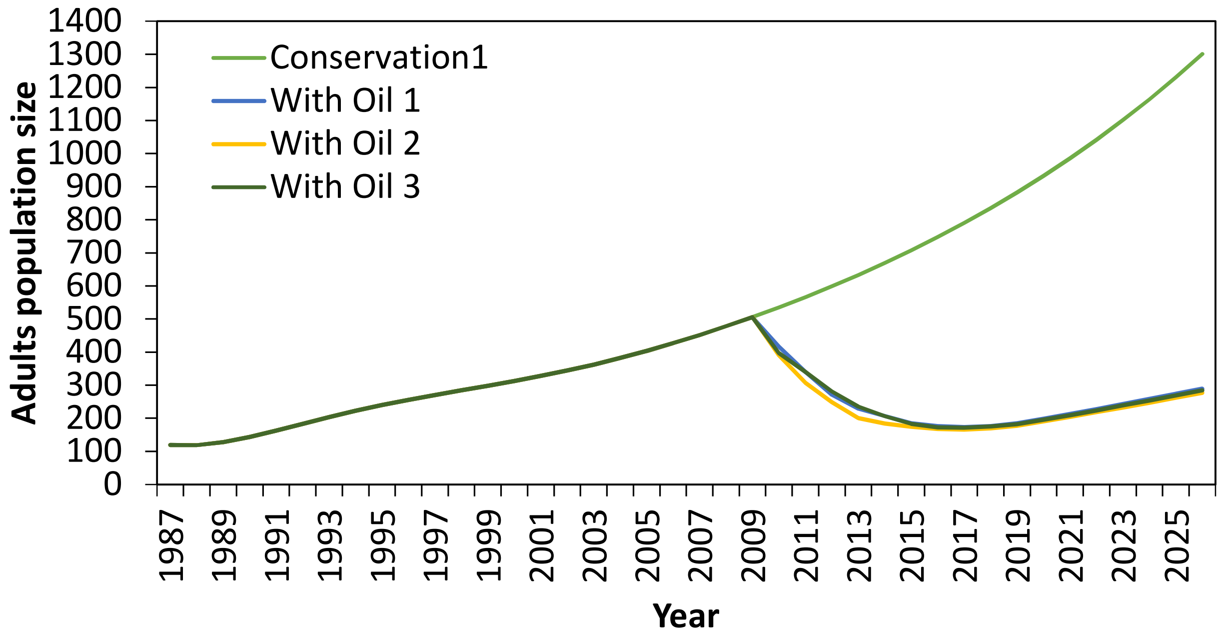

Figure 4. Conservation scenario 1 with and without added oil mortality following DWH oil spill in 2010. Green line represents the loggerhead sea turtle (LHST) population with conservation scenario 1 without added oil effects. With oil 1 (blue), with oil 2 (yellow), and with oil 3 (dark green) lines represent possible LHST population results under conservation scenario 1 with added oil mortality effects following DWH oil spill.

Similar to conservation scenario 1, conservation scenario 2 with added oil mortality effects showed a growth in the population until 2010 when oil mortality as a result of DWH oil spill caused a decrease in the population (Fig. 5). When we compared the effected population in 2026 at the end of the 40-year simulation at approximately 339 individuals to its respective population size without added oil mortality at approximately 1,600 individuals we found this comparison showed a population decrease of 78.8%. As our added oil mortality rate parameter decreased linearly over the 10-year period, we can see that the population slowly began to recover.

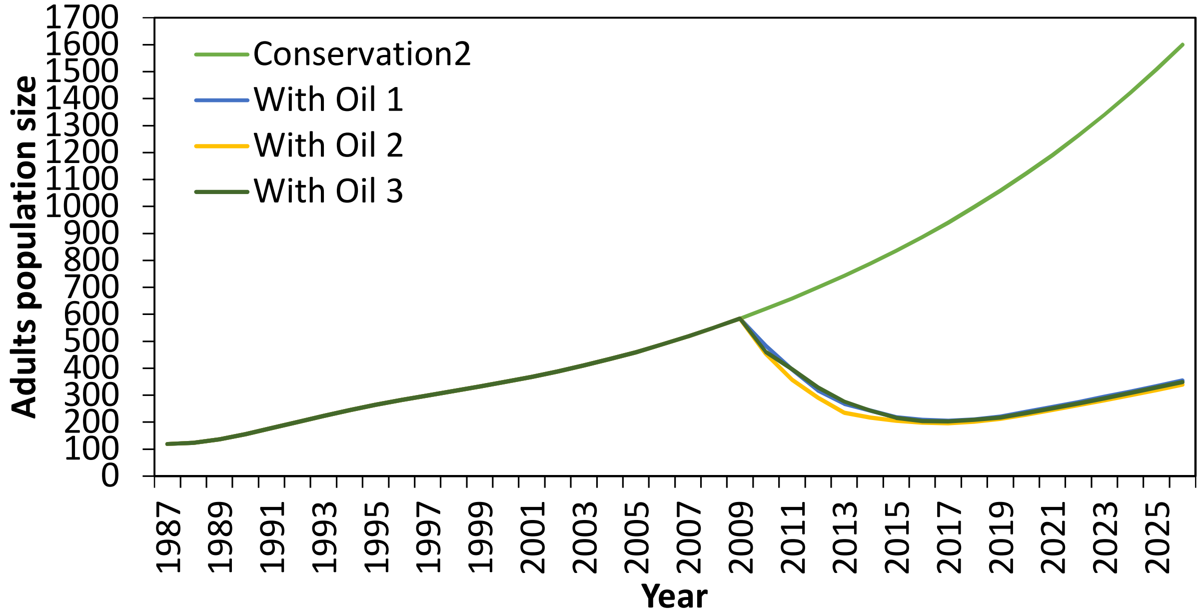

Figure 5. Conservation scenario 2 with and without added oil mortality following DWH oil spill in 2010. Green line represents the LHST population with conservation scenario 2 without added oil effects. With oil 1 (blue), with oil 2 (yellow), and with oil 3 (dark green) lines represent possible LHST population results under conservation scenario 2 with added oil mortality effects following DWH oil spill.

Similar to conservation scenarios 1 and 2, conservation scenario 3 with added oil mortality effects showed a growth in the population until 2010 when oil mortality as a result of DWH oil spill caused a decrease in the population (Fig. 6). When we compared the effected population in 2026 at the end of the 40-year simulation at approximately 91 individuals to its respective population size without added oil mortality at approximately 435 individuals we found this comparison showed a population decrease of 79.1%. As our added oil mortality rate parameter decreased linearly over the 10-year period, we can see that the population slowly began to recover.

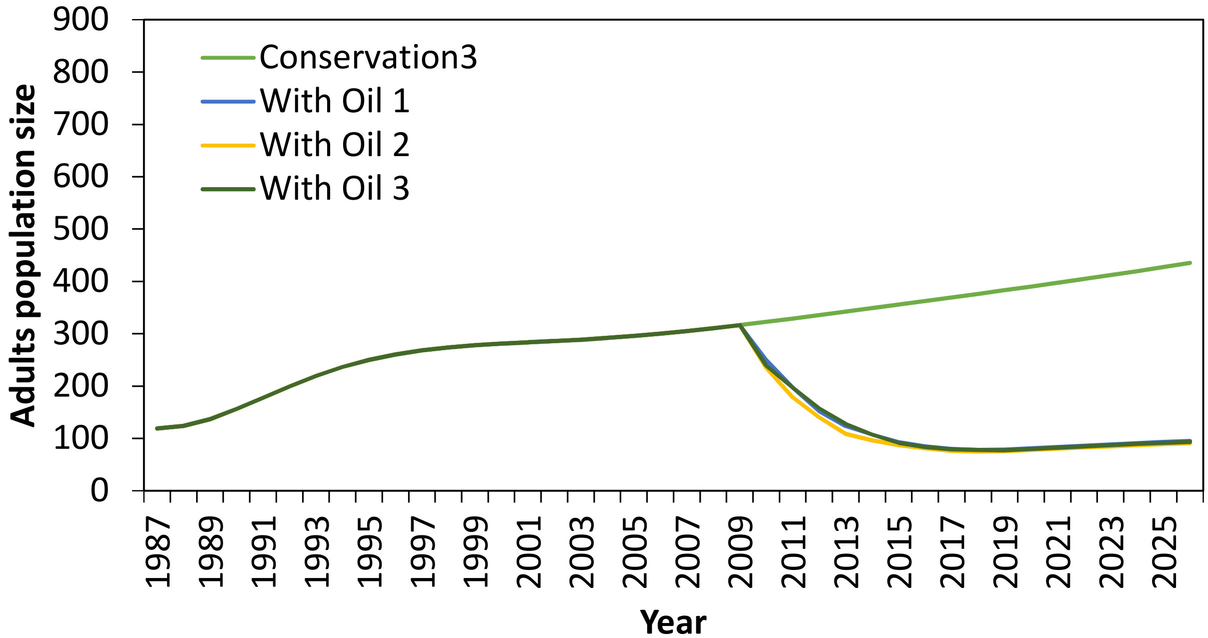

Figure 6. Conservation scenario 3 with and without added oil mortality following DWH oil spill in 2010. Green line represents the LHST population with conservation scenario 3 without added oil effects. With oil 1 (blue), with oil 2 (yellow), and with oil 3 (dark green) lines represent possible LHST population results under conservation scenario 3 with added oil mortality effects following DWH oil spill.

CHAPTER IV

CONCLUSION

Our simulations strongly suggest that if the survival of loggerhead turtle populations in the southeastern United States are similar as proposed by Frazer, then the key to improving the outlook for these populations lies in reducing mortality in the later stages, particularly the large juveniles (Crouse et al. 1987).

It seems many sea turtle biologists can't agree as to where to focus their conservation efforts. According to Crouse et al., current management practices at the time of his 1987 paper appeared to be focused on the least responsive life stage, eggs on nesting beaches. More recently, scientists have opted for saving adults over juveniles, noting that adults have already survived their trying juvenile years are ready to lay their eggs. While it's true that reproductive value is highest in the adults, very few turtles actually make it to these stages to reproduce (Crouse et al. 1987). Alternative methods for conservation of life stages should be made. Looking at our conservation scenarios without added oil mortality, Conservation scenario 2 showed the greatest increase in population numbers over time. From this, we assume that shifting conservation focus towards increasing survivorship in large juveniles/subadults and adults can have the greatest impact in protecting the population over time. Increasing survival in juveniles makes it much more likely that a larger number of sea turtles will survive to reach maturity, therefore magnifying the increased reproductive value of adult life stages (Crouse et al. 1987).

Another thing learned from these simulations is that population strength or longevity doesn't come from sheer numbers alone, but from survival, fecundity, and mortality relationships throughout the life cycle. A decrease in the baseline scenario without added oil effects implies the possibility of the population's extinction despite current conservation efforts. Thus, the presence of large numbers of animals can be deceptive, implying robustness, when in reality such a population might be highly susceptible to perturbations in particular life stages (Crouse et al. 1987).

Our study confirms the work done by Crouse and his colleagues and contributes to our understanding of loggerhead sea turtle population dynamics. We find this especially important when studying anthropogenic events such as oil spills because we can use this foundation to be more confident in our management strategy.

Future work on our project could include exploring the AddOilMorRate function of oil damage through the 10 years from 2010-2019. The relationship might not be linear as we designed in this study. Other functional options could be representing this rate with a convex or concave curve. A concave curve representing a quicker dispersion rate following the spill and that rate slowing over the 10-year time frame. A convex curve representing a slow dispersion rate following the spill and that rate increasing as it approaches the tenth year. A concave or convex curve would be a more accurate representation of oil dispersion rate in nature. Also, long term monitoring for each stage of LHST would be beneficial in order to get a more accurate estimation of survival, mortality, and population size.

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APPENDIX

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