Estimating Degree of Oiling of Sea Turtles and Surface Habitat during the *Deepwater Horizon* Oil Spill: Implications for Injury Quantification

Technical Report
Draft

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Executive Summary

Although adverse effects on marine wildlife exposed to oil have been documented extensively, the *Deepwater Horizon* (DWH) oil spill was unprecedented in extent and duration, and affected habitats and organisms throughout the northern Gulf of Mexico marine ecosystem. In particular, the remote location of the wellhead within deep waters distant from shore meant that organisms such as sea turtles, which inhabit offshore and continental shelf areas, were vulnerable to DWH oil exposures. Thus, different assessment and response approaches were required than those used in previous spills, which occurred closer to shore and in smaller areas. In this report, we describe a novel spatio-temporally explicit approach that used direct observations of oiled sea turtles and satellite-derived surface oil distributions to statistically estimate the probabilities of oil exposure for sea turtles that were present within the footprint area of DWH oil but whose oiling status was unknown. This approach leveraged valuable field-based observations of the extent of oiling on sea turtles and the factors that influenced these observed oil exposures by combining field-based data with satellite-derived measurements of surface oil. We estimated the probability of heavy oil exposure in cases where surface oil data were available, but field-based data were not. Thus, we were able to estimate these probabilities for all turtles documented within the DWH oil spill footprint and time period, which allowed for expanded quantification of total numbers of turtles exposed to, and likely killed by, DWH oil, based on the sample of turtles directly observed in the field. Specifically, the combination of our assignments of probability of heavy oiling to density and abundance estimates estimated for sea turtles in offshore and continental shelf areas allowed us to estimate overall injuries.

We estimated that the DWH oil spill killed approximately 56,000 and up to 166,000 oceanic juveniles and between 4,900 and up to 7,600 neritic sea turtles (i.e., large juveniles and adults). Our approach is conceptually straightforward and uses common geospatial and statistical techniques, which makes it applicable to other situations in which managers must estimate the full extent of oil exposures for marine natural resources based on an incomplete sample.

1. Introduction

1.1 Background

Adverse physical and toxic effects on wildlife exposed to oil have been documented extensively (e.g., Leighton, 1993; Piatt and Ford, 1996; Peterson et al., 2003; Shigenaka, 2003; Munilla et al., 2011; Helm et al., 2015). *Deepwater Horizon* (DWH) oil was no exception; exposure to DWH oil caused a variety of harmful effects on a wide range of species native to the northern Gulf of Mexico (GoM) (e.g., Schwacke et al., 2014; Brown-Peterson et al., 2015). The DWH oil spill, the largest marine oil spill in U.S. history, covered more than 112,000 km^2 of the ocean surface and reached more than 2,100 km of shoreline [Programmatic Damage and Restoration Plan (PDARP) Injury Chapter: Natural Resource Exposure section]. In addition, the remote location of the wellhead, within deep waters distant from shore, posed significant logistical challenges to wildlife response and rescue efforts. Furthermore, it meant that organisms that inhabit offshore areas were especially vulnerable to DWH oil exposures. This necessitated different assessment and response approaches than those used in previous spills that occurred closer to shore and in smaller, more confined areas.

The need for different approaches was particularly true for sea turtles. Although oiling and mortality of sea turtles have been documented for previous spills in various locations around the world, detailed information, especially with regard to adverse effects of oil, is generally sparse (Shigenaka, 2003). After hatching from eggs and entering the ocean, small juvenile turtles associate with convergence zones (i.e., areas where surface currents come together) in open-ocean areas, where they feed, grow, and evade predation for several years (Bolten, 2003). Turtles in this life stage remain at or near the surface, associated with floating material, specifically *Sargassum* habitats (Witherington et al., 2012). The DWH oil spill overlapped with vital habitats for sea turtles, particularly those of small juvenile turtles that typically occur in ephemeral *Sargassum* habitats offshore, at or near the surface (Hu, 2015). The Trustees recognized that the convergence zones would bring together anything floating at the surface, such as *Sargassum*, sea turtles, and oil – and therefore DWH oil would pose a significant risk to turtles in this life stage (Stacy, 2012a). As the spill progressed and oil moved into continental shelf and nearshore areas, the Trustees also recognized that larger, older sea turtles in these areas, and sea turtle nesting beaches, were at risk of exposure to oil as well.

1.1.1 Sea turtle status, life stages, habitat use, and potential exposure to DWH oil in the Gulf of Mexico

Five species of sea turtles inhabit the GoM: loggerheads (*Caretta caretta*), Kemp's ridleys (*Lepidochelys kempii*), green turtles (*Chelonia mydas*), hawksbills (*Eretmochelys imbricata*), and leatherbacks (*Dermochelys coriacea*). Loggerheads, Kemp's ridleys, green turtles, and hawksbills are in the Cheloniidae family (hard shells), and leatherbacks are in the Dermochelyidae family. Loggerheads are listed as "Threatened" under the Endangered Species Act (ESA), while the other four species are listed as "Endangered" under the ESA. Sea turtles in the northern GoM face multiple anthropogenic threats presently, and all populations are depleted relative to historical levels (Wallace et al., 2011).

The sea turtle lifecycle begins with egg-laying on nesting beaches, followed by hatchling emergence and entry into the ocean. Small juvenile turtles are associated with convergence zones in open-ocean areas, where they feed, grow, and evade predation for several years. After this open-ocean or oceanic phase, turtles recruit into continental shelf or neritic areas, where they continue growing to larger sizes over several additional years – or even decades (Bolten, 2003;

Avens et al., 2015). Turtles reach adulthood and mostly remain in continental shelf areas for the rest of their lives. Leatherback turtles are an exception and continue to frequent both the continental shelf and distant offshore waters. Apart from adult females, which come ashore approximately every two or three years to lay eggs several times in a season, sea turtles remain at sea for their entire lives, showing site-fidelity to selected foraging grounds (Shaver et al., 2013; Hart et al., 2014, Vander Zanden et al., 2015). A summary of the sea turtle lifecycle and habitat use by different life stages is presented in Bolten (2003).

Given their lifecycle, sea turtles occupy habitats across geographic areas in the northern GoM during various life stages (Lamont et al., 2015). The pervasive and prolonged nature of the DWH spill and the related response activities overlapped in time and space with sea turtle distributions throughout the northern GoM, from offshore to continental shelf areas and on beaches. Consequently, sea turtle exposure to DWH oil and their resulting injuries affected multiple life stages in offshore areas, across the continental shelf, and in nearshore and coastal areas during 2010; the injuries likely continued for some time after the summer of 2010.

1.2 Assessments of Sea Turtle Exposure to DWH Oil

The Trustees conducted an interdisciplinary suite of surveys to assess exposure and injury to sea turtles from the DWH oil spill, including using information from boat-based rescues and veterinary assessments, aerial surveys, satellite tracking of live sea turtles, recovery of stranded sea turtles, and monitoring of nesting sea turtles. Data collected during boat-based and aerial surveys allowed the Trustees to estimate turtle densities and abundance in the northern GoM during 2010 (Garrison, 2015; McDonald et al., 2015).

1.2.1 Boat-based rescue veterinary assessment operations

During boat-based rescue operations, the Trustees searched offshore areas characterized by surface convergence zones that aggregate floating materials (e.g., *Sargassum* and associated habitat, in which small, oceanic-phase juvenile sea turtles would be expected to live) (Bolten, 2003; Witherington et al., 2012). Rescue operations targeted these areas because oil was expected to accumulate in these areas, thus creating a concentrated risk of exposure to sea turtles (Stacy, 2012a). Between late May and early September 2010, rescue teams operating out of three different ports (Venice, LA; Orange Beach, AL; and Destin, FL) performed active searches on more than 1,200 transects totaling over 4,200 linear kilometers and an area of nearly 200 square kilometers. Because the objective of these operations was to rescue sea turtles, and not to perform scientifically structured surveys, effort was not distributed randomly in space or time. Teams captured nearly 600 turtles, and sighted more than 300 more (Figure 1). More than 80% of the captured turtles were visibly oiled, and of those, a sufficient volume of oil was collected to confirm that 40% were oiled by Macondo oil (Stout, 2014).

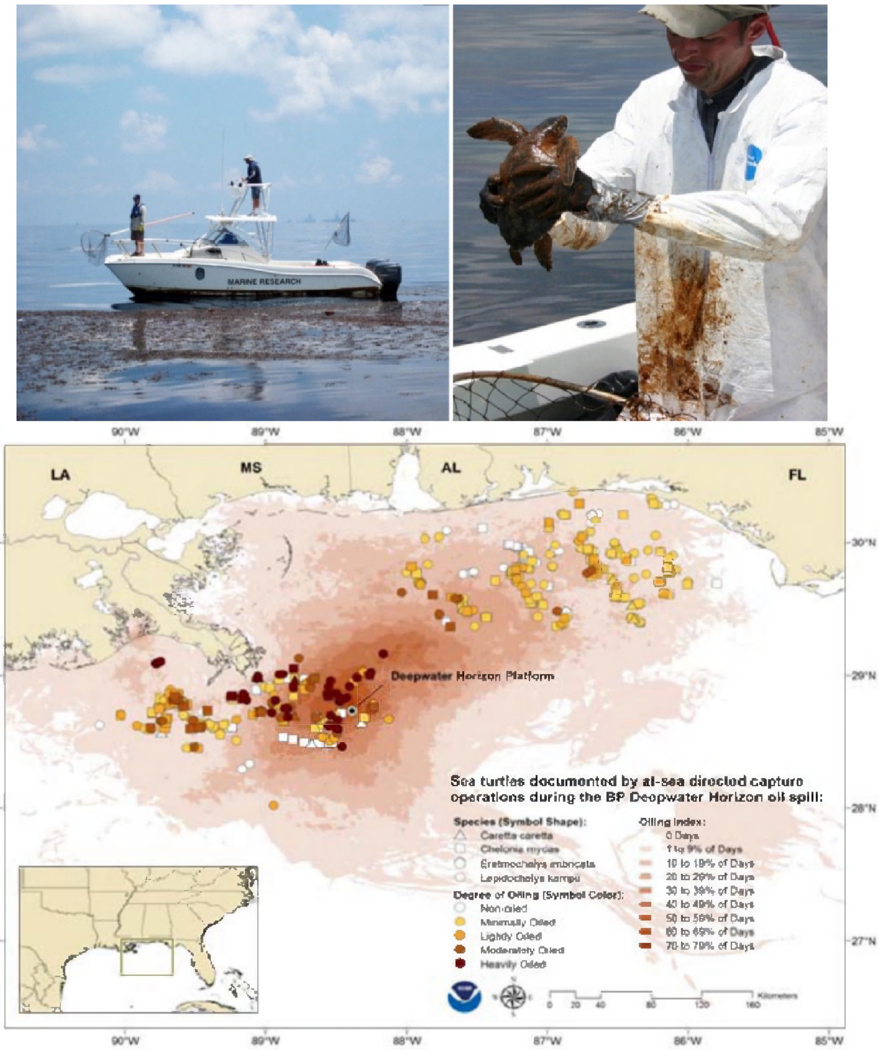

Figure 1. Boat-based rescue efforts documented more than 900 sea turtles in the DWH spill zone. Photos: (top left) Boat-based rescue efforts on search transects within offshore convergence areas that are known habitats for small juvenile sea turtles; (top right) a National Oceanic and Atmospheric Administration (NOAA) veterinarian assessing the condition of heavily oiled sea turtles rescued from oiled surface habitat; (bottom) locations of turtles captured and assessed during rescue operations, shown by species and degree of oiling, overlaid upon cumulative oil days within the overall oiling footprint. Nearly all heavily oiled turtles were found within 90 km of the wellhead, and prior to August 1, 2010.

Photo sources: B. Witherington (top left), T. Hirama (top right).

During rescue efforts, responders also documented a small number of dead, heavily oiled turtles in oiled offshore areas, as well as on beaches. Veterinarians attributed the cause of death to oiling, including aspiration of oil, in those animals that were sufficiently intact for examination, and suspected oiling as cause of death in additional turtles that were severely decomposed or scavenged (Stacy, 2012a).

In addition, veterinarians assessed the conditions of turtles rescued from the northern GoM during the spill (Stacy, 2012a, 2012b). Based on the extent to which turtles' bodies were externally oiled, and the relative amount of oil in oral and nasal cavities of live and dead turtles, turtles were assigned to the following oiling categories: unoiled, minimally oiled, lightly oiled, moderately oiled, and heavily oiled. Among oiled turtles, approximately 58% were minimally oiled, 19% were lightly oiled, 10% were moderately oiled, and 13% were heavily oiled (Figure 2; Table 1).

Figure 2. Photographs of turtles in each oiling category defined by extent of external oiling. Percentages of turtles documented in each category relative to all turtles assessed are shown next to a representative photograph of each oiling category.

Photo source: B. Stacy.

Table 1. Numbers of sea turtles documented by directed capture operations during the DWH oil spill response by degree of oil coverage, species, and proportion with oil observed in oral cavity. "Unknown" turtles did not have sufficient photographic information to be assigned to oiling categories.

Species	Not visibly oiled	Minimally oiled	Lightly oiled	Moderately oiled	Heavily oiled	Unknown	Total
Kemp's ridley	50	141	47	26	51	2	317
Green	49	112	36	17	6	0	220
Loggerhead	6	5	2	3	2	0	18
Hawksbill	5	8	2	1	2	1	19
Total	110	266	87	47	61	3	574
Oil in oral cavity	Not evaluated	49%	76%	93%	97%		

Overall, veterinary assessments and rescue operations documented that exposure of sea turtles by direct contact with oil had numerous negative effects on sea turtle health and survival, including mortality; miring of eyes, nares, and upper gastrointestinal (GI) tract; impeded locomotion and ability to dive, forage, and evade predators; and hyperthermia (Figure 3). Based on this information gathered during rescue operations, physical fouling in surface oil was determined to be the primary route of exposure and cause of immediate adverse effects on sea turtles (Stacy, 2012a). Moreover, these adverse effects of direct contact with oil were expected to increase with the degree of oiling observed.

1.2.2 Sightings of sea turtles during aerial surveys

In addition to the rescue operations that captured oceanic juvenile turtles and directly assessed them for degree of oil exposure, biologists also conducted aerial surveys throughout the northern GoM on the continental shelf (to the 200-m isobaths) in 2010 to locate and count neritic turtles at the surface (Garrison, 2015). Unlike the rescue efforts, these surveys were designed to allow for calculation of estimates of turtle abundance across the survey area throughout the study period, and subsequently for calculation of overall abundance estimates. However, because turtles were sighted from aircraft, they were not captured and assessed for oiling status.

Figure 3. Photographs showing the debilitating effects of physical fouling of oil on sea turtles. Top left: thick, viscous oil on the surface made detection and capture of small juvenile sea turtles difficult. Top right: This heavily oiled, small juvenile sea turtle would not have survived without rescue and rehabilitation because the heavy, viscous oil impeded its movement and its ability to feed and escape predators. Bottom right: heavily oiled turtles were at risk of aspirating oil as shown in this turtle found stranded in Louisiana; a clump of brown oil is present within the trachea (i.e., windpipe). Bottom left: lethally hot temperatures measured at the surface, with dark oil present; to which sea turtles were exposed when at the surface to breath, rest, or feed.

Photo sources: B. Witherington, B. Stacy.

Overall, the Trustees surveyed more than 18,000 linear kilometers along nearly 250 transects, and searched more than 6,600 square kilometers of total area between April 28 and September 2, 2010. Nearly 800 neritic stage turtles (i.e., large juveniles and adults) were sighted at 644 locations along aerial survey transect lines flown systematically over the continental shelf of the northern GoM from April through September 2010 (Garrison, 2015). At some locations, observers saw more than one turtle. Neritic loggerheads were sighted at 338 locations, while Kemp's ridleys were sighted at 212 locations. An additional 97 sea turtles that were unidentified to species were sighted at 86 locations. Nearly 90% of sightings (n = 567 locations) were of single animals; between 2 (n = 46 locations) and 28 animals (n = 1 location) were sighted at the remaining 10% of locations.

These synoptic aerial surveys were structured to allow for statistical estimation of neritic sea turtle density and abundance over time. Surveys were not conducted beyond the 200-m isobaths, and had partial, but limited, spatio-temporal overlap with boat-based rescue operations (Figure 4). However, because these animals were not captured and assessed by veterinarians, their degree of oil exposure was unknown. To determine and quantify injury to turtles observed during aerial surveys, their potential exposure to oil must be estimated.

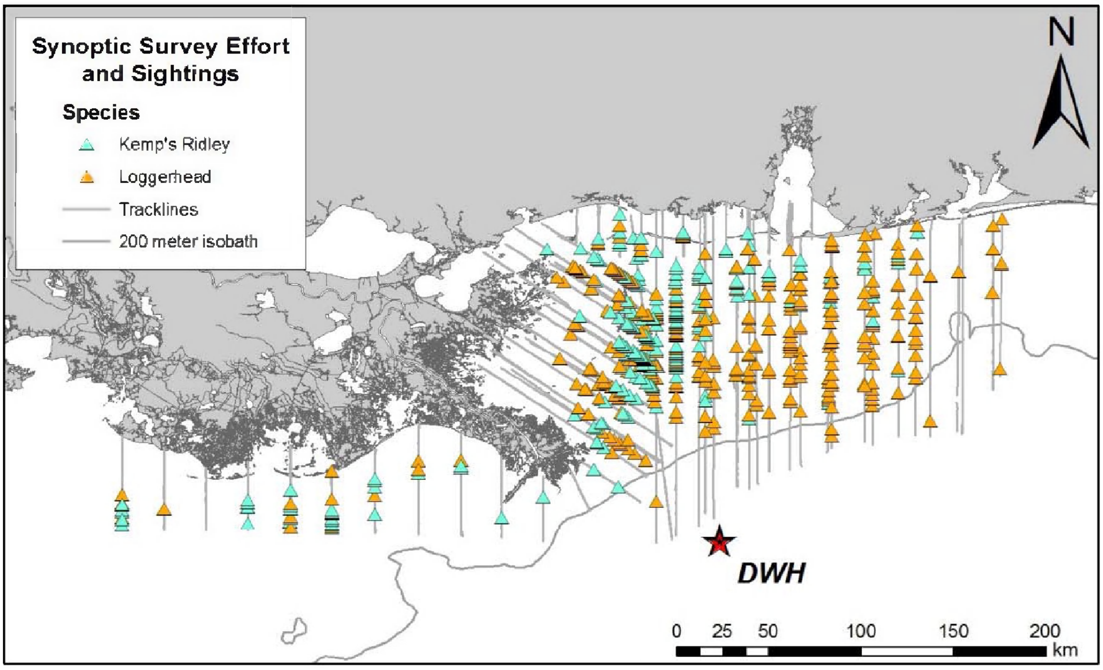

Figure 4. Biologists flew synoptic aerial surveys to document locations of sea turtles within the DWH oil spill footprint. Triangles indicate locations of sightings of Kemp's ridleys (blue; n = 212 sighting locations) and loggerheads (orange; n = 338 sighting locations) along all survey transect lines flown systematically from April through September 2010. At some sighting locations, more than one turtle was observed. Sighting locations of turtles that were unidentified to species are not shown. The location of the wellhead is indicated by the star.

1.3 Study Objectives

In contrast to the oceanic sea turtles that were rescued and then evaluated for oil exposure, neritic turtles observed during aerial surveys could not be directly assessed for oiling status or health condition. This data limitation presented an obstacle to quantification of sea turtle injuries across the full spatial and temporal extent of the DWH oil spill. Therefore, the main goal of this study was to estimate the degree of oiling for neritic turtles observed during aerial surveys using relationships between observed degrees of oiling of rescued turtles and factors that appeared to influence these observed degrees of turtle oiling. In this way, we could assign a likely oiling status to turtles that were observed but not assessed directly, and then conduct a quantitative estimation of oil exposures and the resulting mortality of these turtles wherever and whenever they occurred within the DWH oil spill footprint and time period.

Our analysis focused on the following specific objectives:

1. Estimate mortality based on degrees of turtle oiling observed during rescue operations
2. Describe relationships between remotely sensed surface oil data and other factors and observed degrees of oiling
3. Use these relationships to estimate:
    a. The degree of oiling of turtles that were sighted but not captured and evaluated
    b. Daily probabilities of heavy oiling across the oil spill footprint to provide a spatio-temporal characterization of potential oil exposure in surface waters during the DWH oil spill
4. Combine mortality estimates and numbers of turtles estimated to be in each oiling category to develop a quantitative estimate of total sea turtle injuries.

Specifically, we analyzed multiple datasets to identify various factors that were related to heavy oil exposure, and developed a novel spatio-temporally explicit approach to assign turtles to oil exposure categories. Our results expanded exposure quantification, and thus injury quantification, from directly assessed turtles to all observed turtles to provide a more complete picture of DWH impacts on sea turtles in the northern GoM.

2. Methods

In this study, we synthesized several disparate datasets (e.g., veterinary assessments, spatial and temporal data from boat- and plane-based surveys targeting sea turtles during the DWH spill, satellite-derived surface oil data, and factors that could influence the observed degree of oiling) to develop statistical relationships that could be used to estimate the degree of oiling for turtles that were sighted but not directly assessed. In the sections that follow, we describe specific methods used to develop this analytical framework, as well as results of initial analyses that helped us refine and finalize our analytical framework.

2.1 Severity and Implications of Oil Exposure for Sea Turtles

All sea turtles must spend time at the surface to breathe, rest, bask, and feed, and these fundamental behaviors put turtles at continuous and repeated risk of exposure anywhere that the ocean surface was contaminated by DWH oil. With this in mind, we reviewed veterinary assessments of oiled oceanic juvenile sea turtles (i.e., generally < 25 cm straight carapace length) rescued during response operations in 2010 to characterize the health outcomes for sea turtles based on degree of oiling (Stacy, 2012a). We then scaled mortality estimates for surface-dwelling oceanic sea turtles to deep diving, active swimming, neritic sea turtles (i.e., > 40 cm straight carapace length; Garrison, 2015). We concluded that any turtle in the spill footprint was at risk of some degree of oiling; therefore, a mortality rate of 0% was unwarranted, and all categories were assigned a minimum estimated mortality of 5%. We estimated mortality in increments of 5% to avoid unsupported representation of precision.

This exercise was necessary to provide a biological context for linking observed oil exposures to those estimated for turtles that were not directly assessed but were exposed to similar oil environments (based on remote sensing and statistical modeling). We used the mortality estimates described in this section to develop a quantitative estimation of the total numbers of turtles that died as a result of different degrees of oil exposure (see below).

2.1.1 Oceanic juvenile sea turtles

Many oceanic juvenile turtles that were evaluated following rescue from surface habitats within the DWH oil spill footprint were heavily mired in oil, were lethargic, and were palpably warmer than normal upon collection. Surface oil temperatures were opportunistically recorded and were in excess of 120°F (~ 50°C), which is well above the lethal threshold for sea turtles (Jessop et al., 2000; Drake and Spotila, 2002). Furthermore, miring in oil and exposure to oiled surface habitat would have caused decreased mobility, exhaustion, dehydration, and likely decreased the ability to feed and evade predators (Figure 3).

In addition to adverse effects of external oiling, oil was found in the mouth and esophagus of many turtles and correlated with the degree of external oiling (Stacy, 2012a; Mitchelmore et al., 2015). Based on oral examinations and necropsies, veterinarians documented that oil had adhered to the internal surfaces of the mouth, pharynx, and esophagus. Moreover, indicators of polycyclic aromatic hydrocarbon (PAH) exposure were higher in tissues and other biological samples (e.g., liver, lung, esophagus, gastroenteric tissues, gastroenteric contents) collected from visibly oiled turtles than from non-visibly oiled turtles (Ylitalo et al., 2014).

Based on observations of small juvenile turtles during rescue efforts, physical fouling had the most readily apparent, immediate effect of oil on sea turtles. Small juvenile turtles live, breathe, eat, and seek refuge from predators within the top 2 m of the water column (Bolten, 2003). Therefore, the physical miring that responders observed on heavily oiled oceanic turtles would have prevented turtles from escaping or shedding the thick, sticky, heavy oil (Stacy, 2012a). Conditions from which heavily oiled turtles were rescued were extremely grave; turtles were unlikely to have survived without intervention (Figure 3) (Stacy, 2012a, 2012b). Therefore, we concluded that this heavily oiled condition would have caused death either acutely or chronically, and that any turtle that became heavily oiled but was not rescued would have died.

Oceanic turtles that were exposed to oil but not heavily oiled were still exposed to oil externally and internally (Stacy, 2012a), and likely suffered adverse physiological and toxicological effects of these exposures (Stacy, 2012b; Mitchelmore et al., 2015). Toxicologists developed a range of mortality estimates based on the degree of external and internal oiling and the frequency of observations across these oiling categories. The overall mortality estimate was established as 30% for these less-than-heavily oiled exposures (Mitchelmore et al., 2015).

2.1.2 Neritic sea turtles (large juveniles and adults)

Similar concerns about miring in surface oil were warranted for neritic turtles based on limited observations of impaired, oiled larger turtles during the DWH spill and previous reports of oiling associated with death or stranding (Shigenaka, 2003; Camacho et al., 2013). However, direct observations of degree of oiling afforded by capture and rescue, as well as by veterinary assessments (Stacy, 2012a) and clinical evaluations (Stacy, 2012b), were unavailable for neritic turtles because they were not captured or evaluated directly by response personnel.

Therefore, to establish mortality estimates for neritic turtles, we evaluated the same factors that were considered in developing mortality estimates for oceanic turtles, but we also considered key differences between the data available for oceanic- and neritic-phase turtles. For example, because neritic turtles are active divers that tend to spend the vast majority of their time submerged (Southwood Williard, 2013; Hochscheid, 2014), we reviewed differences between oceanic and neritic turtles in terms of behavior and time-activity budgets and how these might affect extent and severity of exposure to surface oil.

Reports of stranded, oiled, larger turtles indicate that effects can be significant and multisystemic (Shigenaka, 2003; Camacho et al., 2013). Notably, a heavily oiled neritic juvenile encountered during DWH-directed capture operations was found floating with the lateral edge of its carapace and a front flipper above the surface, a condition that did not bode well for survival without intervention (B. Witherington, University of Florida/Disney's Animal Kingdom, personal communication, August 15, 2015). This animal apparently had come into contact with surface oil, and, like heavily oiled oceanic juvenile turtles that were observed by responders, suffered debilitating effects of miring in oil. Thus, the same processes that could lead to an oceanic turtle becoming heavily oiled would also apply to neritic turtles, and the methods to estimate probability of oiling in oceanic turtles – relationships between surface oil data and direct observations of oiled animals – would also apply to neritic turtles. Based on consideration of these factors, we concluded that neritic turtles that were highly exposed to oil would likely have suffered relatively similar adverse effects as those documented for heavily oiled oceanic juveniles.

However, the 100% mortality estimate assigned to heavily oiled oceanic turtles is based on the relationship between small juveniles living exclusively at or near the surface and in areas where surface oil tended to aggregate, and therefore is not directly applicable to neritic turtles, which spend a significantly lower proportion of time at the surface and are not necessarily dependent on convergence areas. To reflect this difference between oceanic and neritic turtles, we scaled the mortality estimates for heavily oiled oceanic turtles by the relative proportions of time that they spend at the surface, compared to the proportions of time that neritic turtles spend at the surface. Using this information, we generated mortality estimates that could be applied to highly exposed neritic turtles. On average, neritic turtles spend approximately 10–15% of their time at the surface (Southwood Williard, 2013; Hochscheid, 2014; Garrison, 2015), whereas oceanic turtles spend more than 80% of their time at or near the surface (Bolten, 2003). Therefore, we discounted the mortality estimates associated with oceanic turtle oiling categories by a factor of between five and eight (80% of time at the surface for oceanics: 10% to 15% of time at surface for neritics, or 80%:10% or 15%). We calculated the mortality rate for heavily oiled neritic turtles to be 10–20%. For neritic turtles that were exposed to oil at lesser degrees, we assumed a mortality rate of 5%; because these turtles were likely exposed to oil to some degree, an assumption of no mortality was not warranted, as described above.

2.2 Spatial Modeling of Oil Exposure Risk to Sea Turtles

In this section, we describe analyses of spatio-temporal relationships between degree of oiling of captured turtles, their capture locations and proximity to the wellhead, and environmental oiling metrics that were used in trial models to estimate degrees of turtle oiling.

2.2.1 Distance from the wellhead, cumulative days of oil, and capture dates

We reviewed information about the date and location of captures relative to the observed degree of oiling to identify potential candidate variables for statistical classification of oiling categories.

Upon initial review of the spatio-temporal distribution of turtles based on the degree of oiling, we performed focused analyses of distance from the wellhead, cumulative days of oil in locations where turtles had been captured (i.e., a proxy for the persistence of oil in a certain location), and capture dates.

More than 90% of heavily oiled turtles were found within 90 km (straight-line distance) of the wellhead. Additionally, all heavily oiled turtles were found before August 1, 2010 (Stacy, 2012a; Figure 5A). Furthermore, a cumulative index of surface oil at capture locations [i.e., oil measured by synthetic aperture radar (SAR; Garcia-Pineda et al., 2009; Graettinger et al., 2015)] increased with the degree of oiling of turtles observed in the field and decreased with increasing distance of turtles from the wellhead (Figure 5B). This index integrated daily SAR data to present the cumulative number of days that SAR detected surface oil across the northern GoM from April through August, 2010 (Garcia-Pineda et al., 2009; Graettinger et al., 2015). We downloaded SAR data used in this analysis from the Environmental Response Management Application (ERMA) in October 2014 and again in June 2015.

For comparison, we plotted the distributions of distances from the wellhead and cumulative SAR days for turtle captures and sightings during rescue operations and aerial survey sighting locations (not the total number of turtles sighted; Figure 6). As described above, there were some locations where observers saw more than one turtle. Overall, more turtle captures or sightings during rescue operations were in close proximity to the wellhead and in locations with high cumulative oiling than turtle sightings during aerial surveys. However, differences between the two survey methods are attributable to differences in their relative spatial extent (rescues, Figure 1; aerial surveys, Figure 4). The non-uniform distribution of rescue efforts in space and time is evident in a trimodal distribution of distances from the wellhead of captured and sighted turtles (Figure 6A). In contrast, distances from the wellhead of turtles sighted during aerial surveys resemble a normal distribution (Figure 6B). Aerial surveys were conducted over a relatively continuous area on the continental shelf (i.e., out to the 200-m isobath), an area that was slightly westward compared to rescue operations. Rescue operations took place further eastward, with rescuers searching three main areas based on operations based out of three different ports.

Based on the observed relationships between the observed degree of turtle oiling and distance from the wellhead, date of capture or sighting, and cumulative SAR days, we used these variables in modeling designed to classify turtles to degrees of oiling, as described below.

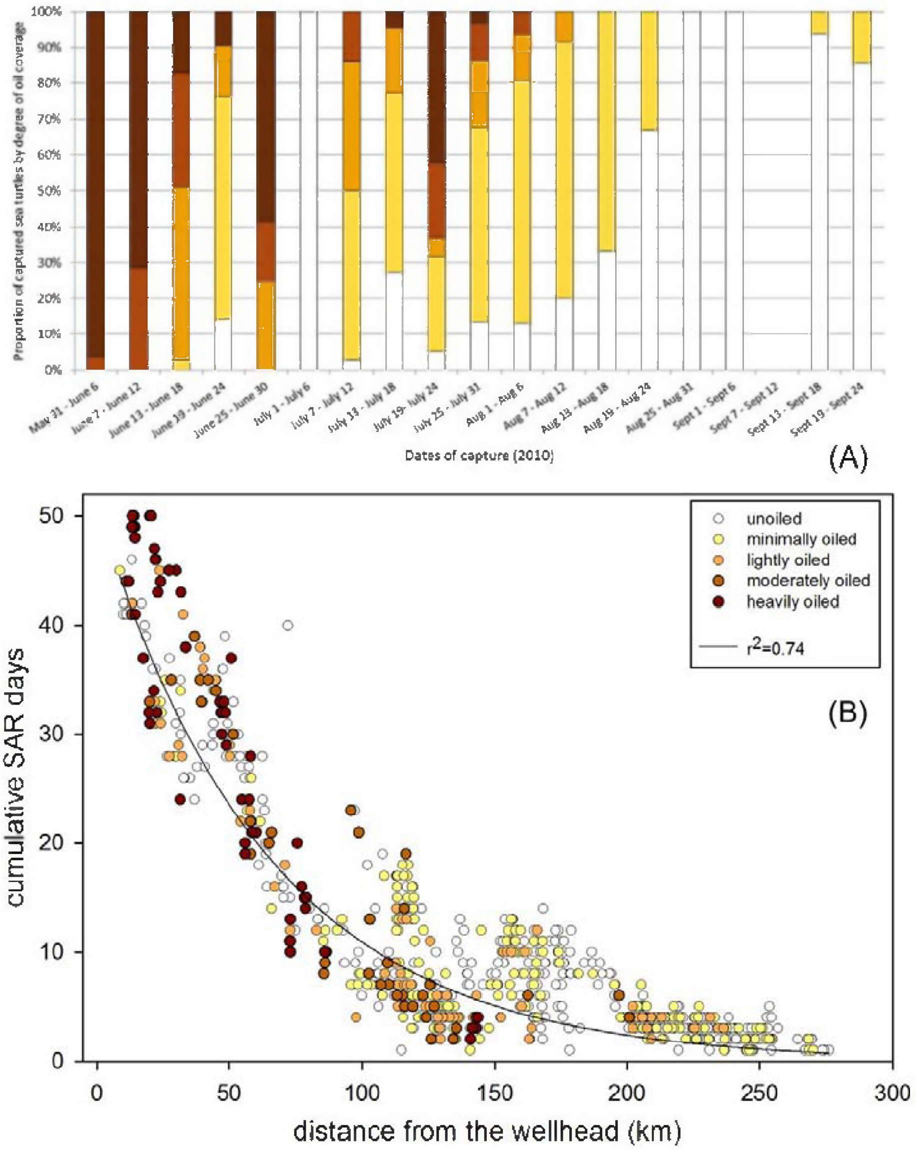

Figure 5. (A): Observations of turtles by degree of oiling shown by capture date during response activities from May to September 2010; (B) Cumulative days oiled based on SAR data plotted by distance from the wellhead. Because of inclement weather and logistical constraints, response efforts were not conducted uniformly during the spill. The symbol colors correspond to the observed degree of oiling of sea turtles collected during DWH response activities. The color scheme for the degree of oiling is similar between the two panels.

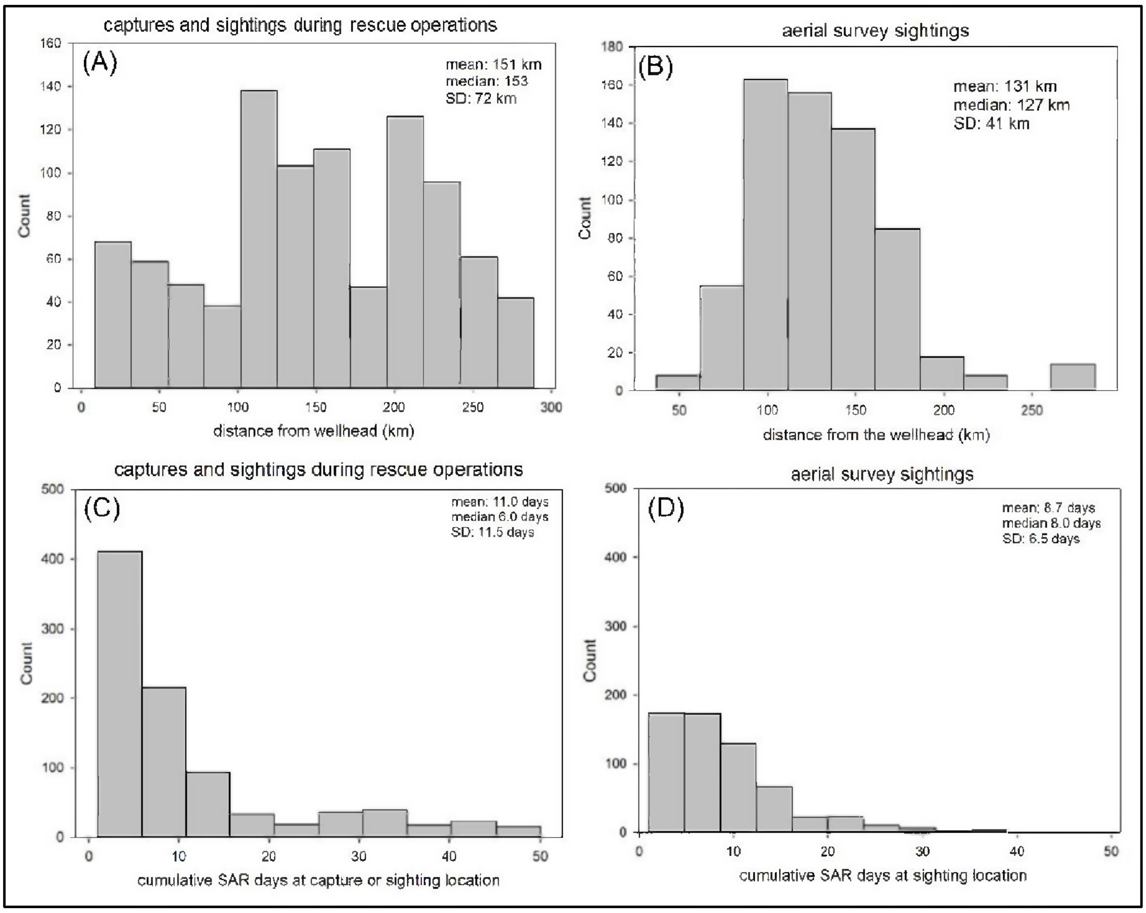

Figure 6. Distance from the wellhead (A and B) and cumulative SAR days where sea turtles were documented (C and D) during rescue operations (A and C) and aerial surveys (B and D).

2.3 Statistical Classification Modeling of Oil Exposure Risk

Field data demonstrated that heavily oiled turtles (1) suffered severe, adverse effects of oil exposure, including death; (2) were observed relatively close to the wellhead; (3) were observed relatively early in the spill period, primarily during the period of free-release of oil before the wellhead was capped; and (4) were captured in areas that had generally higher cumulative oil present during the spill. We explored analytical approaches that could use these relationships to estimate the probability of a turtle being heavily oiled.

2.3.1 Probability of oiling based on exposure to surface oil

All turtles, regardless of life stage, behavior, trophic level, or physiological capacity, must spend time at or near the air-water interface. Field observations and veterinary assessments of oceanic juvenile turtles demonstrated that physical miring in surface oil and oiled surface habitats caused significant harm to sea turtles. Therefore, we concluded that surface oil conditions in locations and at times when heavily oiled turtles were observed were indicative of heavy oil exposure generally. As described in the sections that follow, we developed a model based on this concept to estimate the probability of turtles being heavily oiled, based on remotely sensed surface oil data in the area and at the time preceding a turtle's capture or sighting.

2.3.2 Model framework: Characterizing the surface oil environment using satellite-derived oil data

Given the primacy of exposure to surface oil in describing potential injuries to sea turtles, we developed an approach to analyze turtle captures and sightings in the context of integrated spatio-temporal information about surface oil. Specifically, our goal was to answer the question, "What does it take for a turtle to get heavily oiled?" To answer this question, we quantified the spatial and temporal proximity of sea turtles to surface oil detected by SAR to describe the oil environment before researchers captured a turtle and evaluated its oiling status. Specifically, we counted the number of daily SAR footprints in the time before turtles were captured and in the vicinity of turtle capture locations to estimate the potential exposure of sea turtles to surface oil. We then related the number of SAR intersections to the observed degree of oiling (Figure 7).

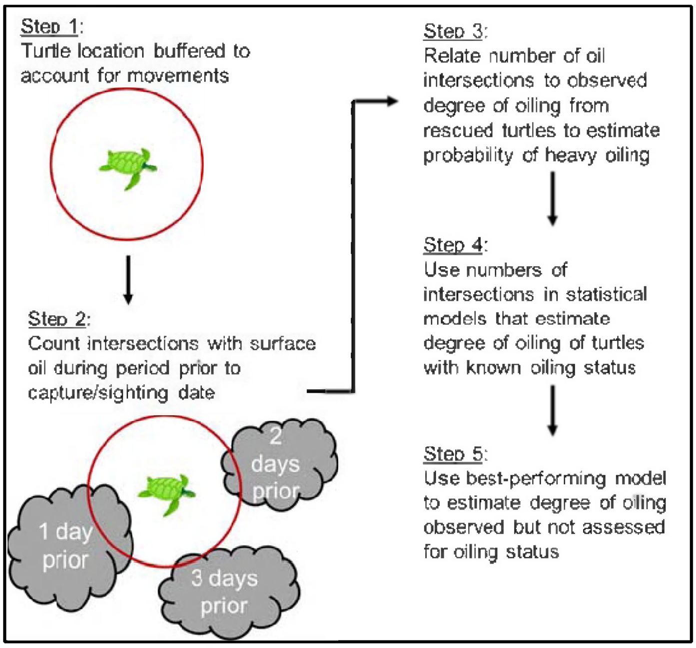

Figure 7. Schematic of the modeling approach to quantify number of SAR intersections for spatio-temporally buffered turtle locations and to use those values to develop statistical models to estimate degree of turtle oiling. A description of the steps appears in the text.

As a first step, we developed several scenarios to quantify spatio-temporal overlap between turtle locations and daily SAR oil footprints. To account for the area that oceanic turtles moved in during the period before researchers found them, either while turtles were actively swimming or were passively drifting in surface currents (Putman and Mansfield, 2015), we modeled circular distance buffers around each turtle location (Figure 7). These spatial buffers also accounted for the movement of oil through the surface environment over time. In addition to these spatial buffers, we included a temporal component by varying the number of days that a spatially buffered turtle location might have intersected with daily SAR footprints before the turtle's capture date (Figure 7).

We constructed multiple spatio-temporal scenarios to characterize patterns in the accumulation of SAR intersections. We performed a cross-factorial analysis of distance (for buffering and overlaying features) and time (i.e., the number of days in the intersection window) relative to turtle locations and capture dates, and used these to build multiple scenarios of intersection parameters based on each time/distance combination. Thus, scenarios were combinations of a spatial buffer around a turtle location and a temporal window before the date of capture, and varied from fine-scale (e.g., 0.5-km buffer, 1 day before capture) to broad-scale (e.g., 10.5-km buffer, 21 days before capture), with spatial buffers increasing 3–3.5 km per week of increased time before capture dates (Table 2).

Table 2. Spatial buffers around turtle locations and temporal windows before turtle capture dates used to quantify SAR intersection quantification

Scale	Spatial buffer around turtle location (radius, km)	Days before capture
Finest	0.5	1
	3.5	7
	7	14
Broadest	10.5	21

These paired spatial and temporal variables were not strictly defined by movement rates of surface-dwelling oceanic sea turtles. Turtles in this life stage typically associate with surface habitats in oceanic-epipelagic (i.e., offshore, at or near the surface) areas that aggregate *Sargassum* and other floating materials (Witherington et al., 2012). Oceanic sea turtles generally remain passively entrained in surface convergence area habitats (Bolten, 2003), but they are also capable of active swimming over long distances and time periods (Putman and Mansfield, 2015). Regardless of whether their travel is passive or active, the direction, magnitude, and speed of their movements can vary tremendously (Mansfield et al., 2014; Putman and Mansfield, 2015). Oceanic turtles can travel tens to possibly hundreds of kilometers in days or weeks, but predicting the directionality, magnitude, and shape of the area that they could have covered in the time before being rescued by response crews was beyond the scope of this assessment. In addition, because we needed to use the same approach for larger neritic turtles (i.e., large juveniles and adults), we chose values that would be applicable to both life stages. Therefore, we constructed spatio-temporal scenarios that would both (1) conservatively estimate the area within which oceanic and neritic turtles might have been within a given time period, and (2) be meaningful within the spatio-temporal scale of the DWH oil spill and oil footprint.

The spatio-temporal scales and general approach to quantifying SAR intersections are biologically reasonable for multiple reasons. First, the total area that we included within the broadest-scale circular spatial buffer around turtle capture locations was approximately 350 km^2, which was between estimates of high-use areas (reported as 50% kernel density estimates; i.e., a method used to identify one or more areas of disproportionately heavy use within a home range boundary) for adult female loggerheads (100.7 $km^2 \pm 141.8$ km^2; Hart et al., 2014) and Kemp's ridley turtles (660.8 $km^2 \pm 899.4$ km^2; Shaver et al., 2013). Second, oceanic turtles in the northern GoM tend to orient their movements to remain near the continental shelf in the northern GoM rather than drifting passively into the open ocean in the central GoM (Putman and Mansfield, 2015). This is relevant because we assumed that, before their capture, turtles were within 10.5 km of the location at which they were captured, and therefore would have been exposed to oil present in the northern GoM during that period.

2.3.3 Model testing: Quantifying intersections between turtles and SAR surface oil

Following the method describe above, we quantified the number of SAR intersections under the spatio-temporal scenarios shown in Table 2 for each turtle that had been captured and evaluated for determination of degree of oiling. In general, the number of intersections increased with an increasing spatial buffer, but the number of intersections increased even more with an increasing period before capture. This is an intuitive result: increasing the spatial buffer only increased the likelihood that a particular intersection would occur and be counted, whereas increasing the temporal window increased the total number of possible oil footprints that a turtle could have intersected. It is worth pointing out that the spatio-temporal scenarios are nested (i.e., as scenarios increase in spatial and temporal scale, each succeeding scenario includes the spatial and temporal scales of the immediately finer-scale scenario). Thus, the broadest-scale scenario (10.5-km buffer, 21 days before capture) contains all SAR intersections tallied in finer-scale scenarios for the same turtle location and capture date. Instead of simply using the broadest-scale scenario that would produce the highest number of intersections, we evaluated multiple scenarios. We did this because we had no *a priori* knowledge of the underlying spatial and temporal relationships between SAR data and degree of oiling of sea turtles. Examining results from multiple scenarios allowed us to explore whether any scenario best described how turtles became oiled to varying degrees.

In general, numbers of intersections increased with the degree of oiling, such that heavily oiled turtles had more SAR intersections than other oiling categories in all spatio-temporal scenarios

(Figure 8). At the finest-scale scenario, which could be considered an indication of probability of acute oil exposure immediately before capture, no unoiled turtle had an intersection with SAR surface oil data, and more than 60% of oiled turtles with a SAR intersection at this scale were heavily oiled (Figure 8A). The extremely high proportions of turtles in low oiling categories in the finer-scale scenarios might reflect low probabilities of oil exposure immediately before capture. In contrast, all heavily oiled turtles had at least one SAR intersection in the 3.5-km, 7-day scenario (Figure 8B); at least three intersections in the 7-km, 14-day scenario (Figure 8C); and no fewer than nine SAR intersections in the broadest-scale scenario (10.5-km, 21-day scenario; Figure 8D).

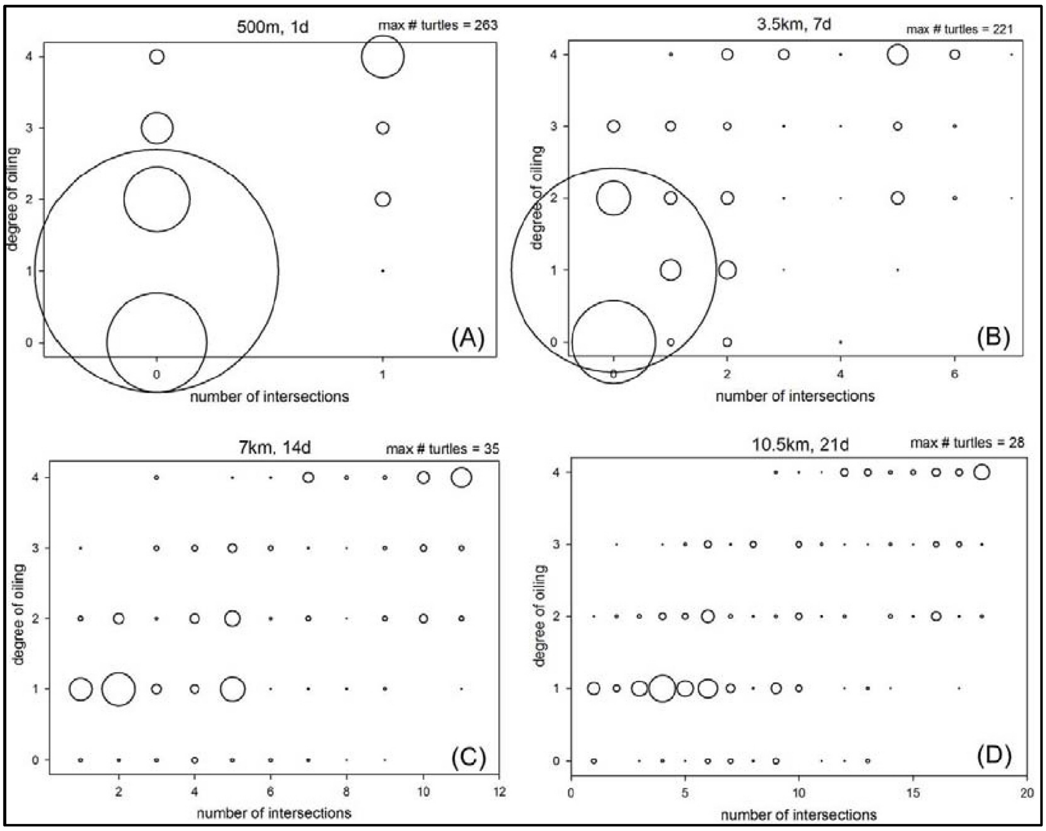

Figure 8. Observed degree of oiling of turtles rescued during the DWH oil spill generally increased with the number of intersections with surface oil footprints between capture locations and dates, across spatio-temporal scales; 0 = unoiled, 1 = minimally oiled, 2 = lightly oiled, 3 = moderately oiled, 4 = heavily oiled. (A) 0.5-km radius buffer around turtle locations, 1 day before capture (finest scale); (B) 3.5 km, 7 days; (C) 7 km, 14 days; (D) 10.5 km, 21 days (broadest scale). Size of circles corresponds to the relative number of turtles for a given combination of number of intersections and oiling category; circle sizes in all panels are on the same scale.

2.4 Estimating Turtle Oiling Categories Using Statistical Classification Models

In this section, we describe our investigation of alternative statistical approaches to develop a model to estimate the degree of oiling of turtles evaluated in the field based on the oil environment in the area and time before captures or sightings of turtles. Our general hypothesis was that turtles found at locations with recent histories of closer and more persistent surface oil would be more likely to experience greater degrees of oiling. To test this general hypothesis and develop a model to classify the oiling status of turtles, we performed the following steps that we discuss in more detail below:

1. We methodically examined several variables in multinomial models [ordinal logistical regression and classification and regression trees (CART)] that incorporated different combinations of potential explanatory variables to explain observed oiling categories

2. We then evaluated the performance of models by comparing misclassification rates of estimated oiling categories relative to the actual oiling categories of the same turtles

3. By comparing performance and behavior among models, we were able to identify the most important explanatory variable and simplify our classification scheme from multinomial (i.e., 5 oiling classes) to binomial (i.e., probability of being heavily oiled)

4. Using this binomial logistic regression approach, we estimated the probability that turtles sighted, but not evaluated for oiling status, were heavily oiled based on the number of SAR intersections in spatially and temporally proximate environments.

2.4.1 Ordinal logistic regression and CART models

Our statistical investigation involved methodically examining relationships between various combinations of candidate variables and degree of turtle oiling. During this investigation, we tried to identify one or more models that performed well as a predictive tool while remaining parsimonious. We investigated two general modeling approaches: ordinal logistic regression and nonparametric CART. In general, both approaches use explanatory variables to classify individual data points into classes or categories (e.g., see Lemon et al., 2003, for more detailed information about these modeling approaches).

First, we constructed multiple models that incorporated different combinations of candidate variables, including distance from the wellhead, elapsed days (i.e., number days between the beginning of the spill and the capture date), cumulative SAR days at the turtle capture location, and one or two different SAR intersection scenarios. We used these sets of candidate variables in both ordinal logistic regression and CART models to generate estimates of degree of turtle oiling for further evaluation.

To compare relative performance among candidate models, we quantified misclassification rates of estimated oiling categories, compared to the known oiling categories for the same dataset (Figure 9). Specifically, we compared misclassification rates (i.e., the percent of turtles whose estimated oiling categories either underestimated or overestimated their actual oiling categories) within and among oiling categories, and between logistic regression and CART results. When considering all oiling classes, the overall misclassification rates for the majority of models were consistently in the range of 30–40%, and misclassifications were evenly divided between overestimates (i.e., model predicted an oiling class higher than actual) and underestimates (i.e., model predicted an oiling class lower than actual).

Upon closer examination of misclassification rates within individual oiling categories, we found that the various regression models and CART models provided reliable classifications of extreme oiling categories [i.e., heavily oiled (class 4) and minimally oiled (class 1)], but provided less reliable classification among the lower oiling classes (i.e., lightly and moderately oiled, classes 2 and 3, respectively; Figure 9). These statistical results reflected the difficulty in objectively classifying turtles in these lower oiling categories based on field observations and notes (Stacy, 2012a). In addition to these factors, the heavily oiled category was the only oiling category that was clearly associated with turtle mortality. For these reasons, we restructured our multinomial classification scheme (i.e., 5 oiling categories) to a binomial classification scheme in which we focused on distinguishing the heavy oiling category from all other classes. In essence, this approach estimated the probability of turtles being heavily oiled.

To orient this binomial classification approach, we inspected the results of the CART models that used several splitting variables to classify turtle oiling categories to determine whether any variables were selected more frequently or were better at classifying turtles into oiling categories than others. CART models consistently selected the broad-scale SAR intersection scenario (10.5 km, 21 days) to split turtles into two initial "heavily oiled" and "not heavily oiled" nodes, and final classification trees always included this variable. Therefore, we ran a CART model using only two response classes – heavily oiled or exposed but not heavily oiled – and the number of SAR intersections in the 10.5-km, 21-day scenario as the only splitting variable. Results of this CART model demonstrated that this sole variable classified all heavily oiled turtles successfully.

In our final step, we estimated the probability of each turtle being heavily oiled using a parsimonious binomial logistic regression with the number of SAR intersections in the 10.5-km, 21-day scenario as the only independent variable. We then applied the results of this model to estimate the probability of heavy oiling for all turtles that were captured or sighted during boat-based rescue operations and aerial surveys. The estimates of heavy oiling probability were not generated for each species separately, but rather for sea turtles generally.

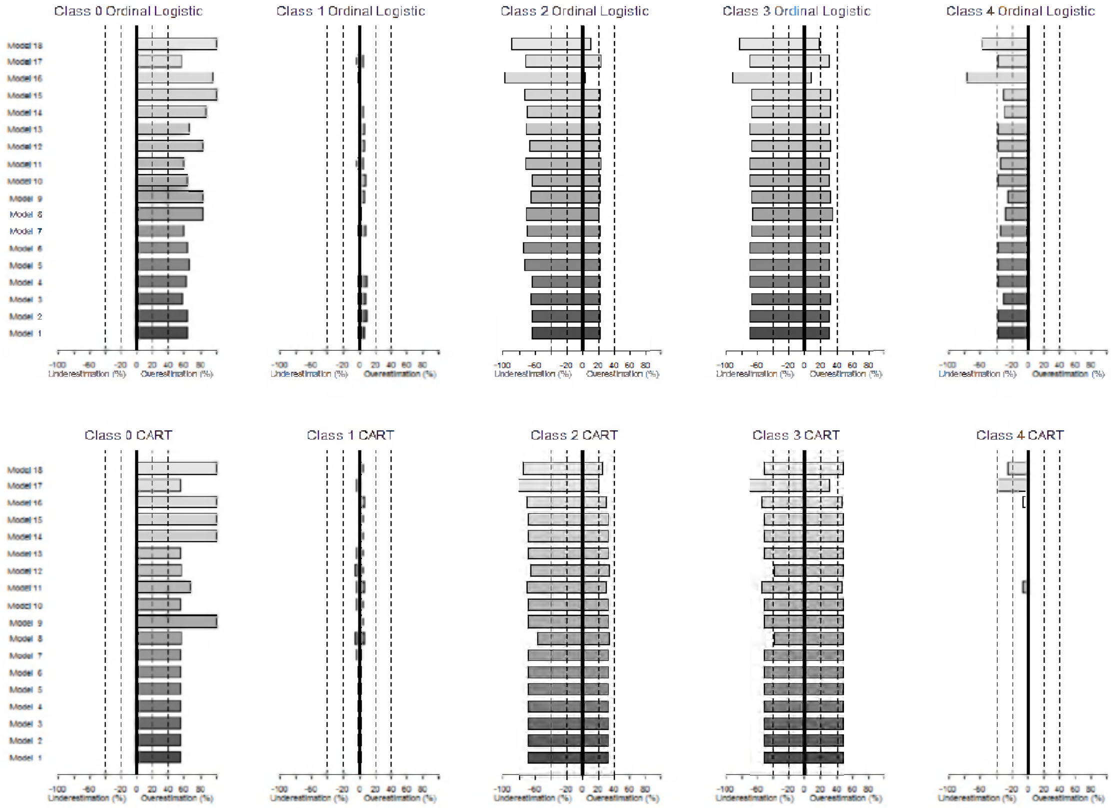

Figure 9. Misclassification rates of ordinal, multinomial logistic regression models (top row) and CART models (bottom row) that incorporated 18 different combinations of explanatory variables (see text for example variables) to estimate oiling categories for turtles whose actual oiling categories were known. Each vertically paired set of classification results are for a specific oiling category; class 0 = unoiled, class 1 = minimally oiled, class 2 = lightly oiled, class 3 = moderately oiled, class 4 = heavily oiled. The x-axes indicate the percent of turtles whose estimated oiling categories either underestimated or overestimated their actual oiling categories (where 0 = correct classification). Thus, the smaller the deviation from 0, the better the classification rates of particular oiling categories by particular models. Both logistic regression and the CART model accurately classified extreme oiling categories [minimally (class 1) and heavily oiled (class 4)], but generally misclassified intermediate oiling categories [lightly (class 2) and moderately oiled (class 3)]. See text for more details.

2.5 Daily Probabilities of Heavy Oil Exposure across the DWH Footprint

We used the above analysis to generate spatial surfaces of daily heavy oiling exposure probabilities across the entire DWH oil footprint. This adaptation of our oiling probability model provided a generalized spatio-temporal description of probabilities of heavy oil exposure – but not necessarily injuries related to those exposures – at the sea surface that could be applicable to any marine resource that used surface habitats during the DWH oil spill.

First, instead of turtle capture/sighting locations and dates, we used centroid points of a 5-km fishnet grid as the input points; eligible centroids were those at any date within 10.5 km of any SAR footprint that did not intersect land. Specifically, we calculated the number of intersections between points within the grid and daily surface oil footprints between April 23 and August 11, 2010 (i.e., the range of days for which SAR data were available; Figure 10). The quantification of intersections between surface oil and grid cells used the same spatial and temporal buffering procedure used on the turtle observation data, but used only the broadest-scale scenario (i.e., 10.5-km buffer, 21-day window). This approach produced daily probabilities of heavy oiling, as described by the relationship between the observed degree of turtle oiling and the oil environment before a turtle's capture – across the entire cumulative oil footprint.

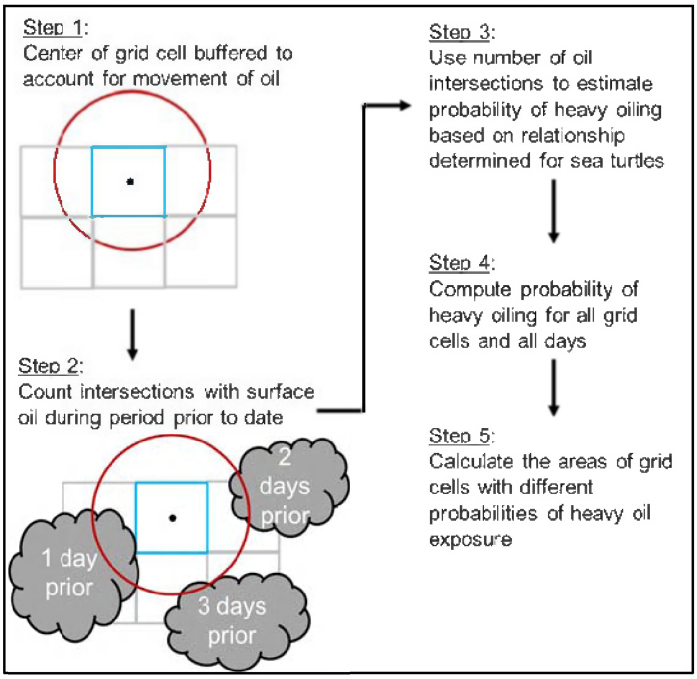

Figure 10. Schematic of the modeling approach to estimate probability of heavy oil exposure across the cumulative oil footprint, using the same process used to estimate heavy oiling probability for sea turtles. A description of the steps appears in the text.

2.6 Assumptions in Our Modeling Approach

It is worth noting three important assumptions about our approach; these assumptions influenced our calculation of the probability of turtles being heavily oiled. First, the surface oil data used in the model did not include any information about the relative thickness of oil in time and space. Therefore, the correlation between the proximity of surface oil and the degree of oiling observed on turtles was based solely on the presence of oil on the sea surface in a given place and time. Second, the model counted the number, not the extent or degree, of intersections between turtle location and surface oil. However, exposure risk probably varied non-uniformly with time at the surface. For example, if a turtle simply surfaced within an oil slick, even if it spent little time at the surface, it would have been exposed via inhalation, direct contact, ingestion, aspiration, etc. Third, the model was fitted to the relationship between surface oil and observed degree of oiling of small juveniles; when estimating probabilities of heavy oiling for larger turtles, the model assumed that the processes that governed heavy oil exposure were comparable for larger turtles.

We concluded that these three assumptions were reasonable because (1) all turtles, regardless of size, must spend significant time at the surface – while they were at the surface in areas that consistently had oil present, turtles would have been exposed; and (2) the number of SAR intersections and observed degree of oiling showed a significant positive relationship (Figure 8), which indicated that the presence of surface oil was likely positively correlated with other factors, such as oil thickness, that may have influenced turtle oiling.

2.7 Quantitative Estimation of Sea Turtle Injuries

The final step was to estimate sea turtle mortality. We did this by combining mortality estimates by oiling category, probabilities of heavy oiling according to the model, and turtle abundance in the DWH oil spill footprint and time period (Figure 11).

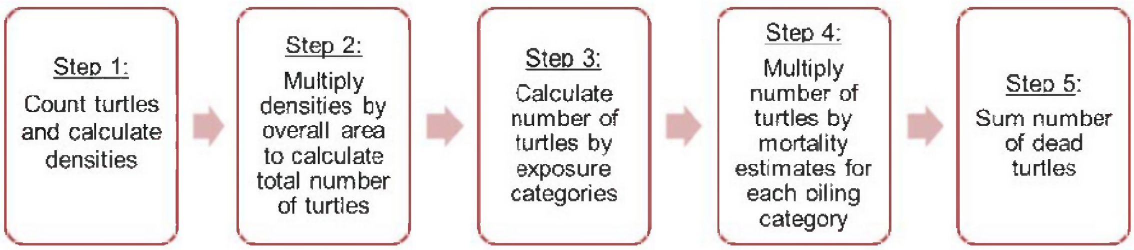

Figure 11. Schematic illustrating the process for estimating sea turtle mortality based on the sample of turtles observed within the footprint and time period of the DWH oil spill. The steps are described in more detail in the text.

First, statisticians used the rescue and sightings data to estimate turtle densities within areas that were searched by boat-based rescue operations (McDonald et al., 2015) or by aerial surveys (Garrison, 2015).

Second, to estimate the total number of turtles present within the DWH oil footprint, we applied turtle densities to areas that were not directly searched based on environmental similarities between searched and unsearched areas. We assumed that the environmental conditions of searched areas were associated with observed densities, and thus that observed densities could be extrapolated to environmentally similar, unsearched areas (see Garrison, 2015, for details).

Third, we categorized turtles by observed or estimated degrees of oiling. Observed degrees of oiling were based on veterinary assessments of rescued turtles, as described in Section 2.1.1. Estimated degrees of oiling were derived from the modeling approach described above (i.e., probabilities of heavy oiling were based on the relationships between observed turtle oiling categories and proximity to surface oil in areas where turtles were documented during the oil spill; see Sections 2.4 and 2.5).

Fourth, the total number of turtles in each oiling category was multiplied by mortality estimates for each oiling category (Section 2.1).

Fifth, and finally, the estimated total number of dead turtles was summed across oiling categories.

Below, we describe in more detail how we performed these calculations using data collected during rescue and survey operations for oceanic sea turtles and neritic sea turtles, respectively.

2.7.1 Oceanic sea turtle injury quantification

To calculate the number of oceanic sea turtles (not species-specific) by degree of oiling, we multiplied densities of heavily oiled turtles and non-heavily oiled turtles estimated within searched areas (McDonald et al., 2015) by the cumulative areas that had non-zero probabilities of heavy oil exposure (Section 2.5). This approach assumed that average turtle densities reflected both spatial and temporal variation in turtle densities, and that the DWH oil footprint encapsulated an average mix of turtle habitat and non-habitat areas (McDonald et al., 2015). This calculation produced abundance estimates of heavily oiled turtles and non-heavily oiled turtles. We assumed that there was a 100% probability of mortality for oceanic turtles estimated to be in the heavily oiled category (see Section 2.1.1).

We then multiplied densities of turtles in non-heavily-oiled categories by the total area defined above. Next, we multiplied this total abundance by the probability values themselves to estimate the number of turtles subject to heavy oil exposure. In this way, the calculation of density-area probability of heavy oiling provided estimates of numbers of turtles with a high probability of heavy oil exposure throughout the spill zone. This number of juvenile turtles was considered heavily oiled, a condition directly linked to 100% mortality (Section 2.1.1, this report).

The remainder of turtles from this calculation (i.e., the difference between total abundance of turtles in a given area and those estimated to be in the heavy oiling category) represented turtles subject to less-than-heavy oil exposure. We applied the mortality estimate for non-heavily oiled turtles (30%; Mitchelmore et al., 2015) to this number of turtles to estimate the number of turtles that would have died from less-than-heavy oil exposure.

2.7.2 Neritic sea turtle injury quantification

To estimate total abundance and exposure of neritic sea turtles, the Trustees performed similar calculations to those described above for oceanic turtles, but with important modifications. In contrast to rescue efforts to capture and evaluate oil exposure of small juvenile sea turtles, neritic turtles could not be directly assessed for oiling status or health condition because they were sighted from aircraft and not evaluated directly. Thus, we estimated the degree of oiling for these animals using the statistical relationship between observed degrees of oiling of rescued turtles and number of SAR intersections for each buffered turtle sighting location, as described in Section 2.4. Garrison (2015) calculated density estimates per grid cell per survey, and incorporated the probabilities of heavy oil exposure that we calculated for individual turtles that were sighted during surveys. In this way, when the densities were multiplied by the survey area to calculate turtle abundances per survey period, we also calculated the number of heavy and non-heavy oil exposures at these spatial and temporal scales (Garrison, 2015).

This approach provided estimates of the numbers of large juvenile and adult sea turtles (not species-specific) in continental shelf waters with a high probability of heavy oil exposure throughout the spill zone. As described above for oceanic turtles, the remainder of turtles from this calculation (i.e., the difference between total abundance of turtles in a given area and those estimated to be in the heavy oil category) represented large juvenile and adult turtles subject to less-than-heavy oil exposures. These calculations provided estimates of turtle abundance by exposure categories. We then applied the mortality estimates described in Section 2.1.2 to heavily oiled (10–20%) and less-than-heavily oiled (5%) turtles to estimate total neritic sea turtle mortality.

3. Results and Discussion

Our goal in this study was to combine empirical and remotely sensed data to estimate the degree of oil exposure and related injuries for oceanic and neritic sea turtles across the DWH oil spill footprint and time period. Below, we present the results of our probability modeling, and the resulting quantitative estimate of sea turtle mortality.

3.1 Probabilities of Heavy Oiling for Sea Turtles

The binomial logistic regression using the broadest-scale SAR intersection scenario as the only independent variable produced probabilities of heavy oiling for all sea turtles whose locations were documented within the DWH spill footprint. Specifically, this model described the relationship between the number of SAR intersections and the probability of heavy oiling as what resembled a sigmoid function (Figure 12). The model estimated very low probability of heavy oiling (< 0.01) when the number of SAR intersections was fewer than seven; the model estimated an increased probability of heavy oiling (51.1%) when the number of SAR intersections was nine or higher (Figure 12). This threshold corresponds to the minimum number of SAR intersections for any heavily oiled turtle (Figure 8D).

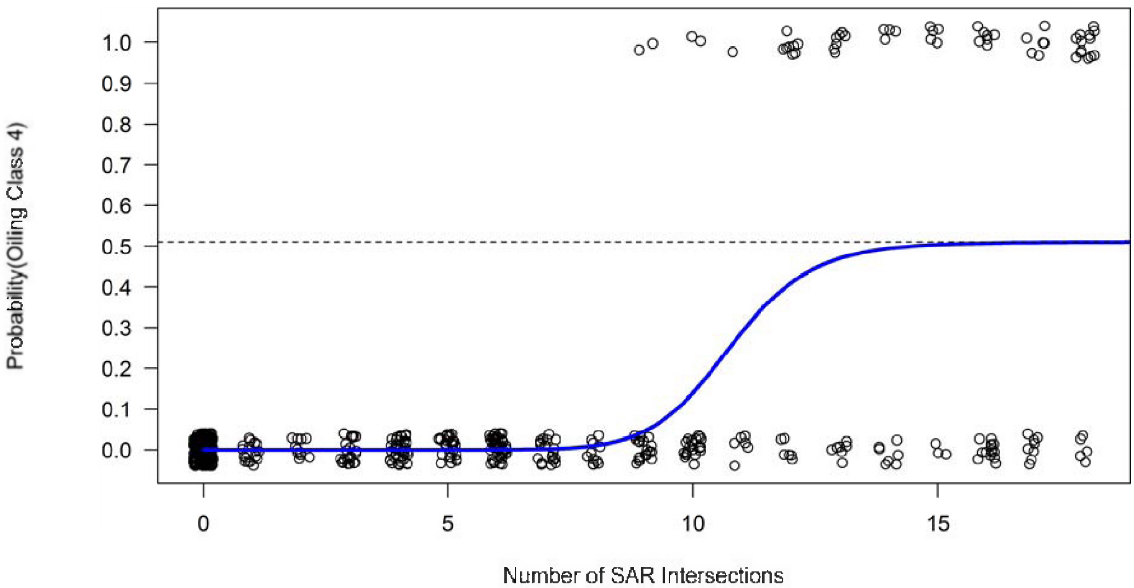

Figure 12. Results of binomial logistic regression using number of SAR intersections with spatio-temporally buffered turtle locations as the sole independent variable. The model estimated probability of heavy oiling for turtles of known oiling status (i.e., those captured and directly evaluated during rescue efforts). Data points are actual oiling classes of turtles. Oiling class 4 = heavily oiled, oiling classes 0–3 = exposed but not heavily oiled (i.e., unoiled, minimally oiled, lightly oiled, and moderately oiled). Maximum probability of heavy oiling was 0.51. Blue line indicates the model estimates of probability of heavy oiling as a function of number of SAR intersections.

3.1.1 Probabilities of heavy oiling: Oceanic versus neritic turtles

We compared the number of SAR intersections and probabilities of heavy oiling estimated for oceanic turtles (i.e., small juvenile turtles captured or sighted in surface habitats during boat-based rescue efforts) with those estimated for neritic turtles (i.e., large juvenile and adult turtles that were sighted in continental shelf waters during aerial surveys) (Figure 13). Distributions of SAR intersections and heavy oiling probabilities were left-skewed for both survey datasets; only 22% of boat survey turtles and 12% of aerial survey turtles had nine or more intersections [i.e., the minimum number of intersections for turtles evaluated to be heavily oiled in the field (Figure 8D)]. Proportionally fewer turtles sighted during aerial surveys had high probabilities of heavy oiling compared to turtles documented during rescue operations. This was probably because aerial surveys were conducted on the continental shelf and in many areas that were more than 100 km from the wellhead and not as affected by surface oil as some areas searched by boat-based rescue crews (Figures 1 and 4). However, it is possible that heavily oiled neritic turtles were more difficult for plane-based observers to see, particularly if oiled turtles were surfacing in an oil slick. Indeed, McDonald et al. (2015) calculated different sightability functions for turtles captured during rescue operations based on oiling category, such that the distance at which observers could reliably see turtles declined with increasing oiling category. However, because the oiling status of neritic turtles was not detectable, the possibility that oiling status might have influenced detection of turtles by observers could not be explored further.

3.1.2 Probabilities of heavy oiling over time

Numbers of SAR intersections and heavy oiling probabilities also showed similar temporal relationships, with highest values for both variables between late May and early July, and then rapid declines from July into August and later in 2010 (Figure 14). These trends reflected patterns of oil movement across the northern GoM. Surface oil footprints peaked in size in June 2010, and began to dissipate in mid- to late July 2010 after the well was capped and oil finally ceased flowing into the ocean.

However, this pattern is also partially an artifact of there being no SAR data after August 11, 2010. This means that while turtles documented after August 11 still could have accumulated SAR intersections and had some probabilities of being heavily oiled, those values would have decreased rapidly without available SAR data. Instead of truncating our datasets at the last day of available SAR data, we analyzed the complete set of captures and sightings data for the entire study period (into September 2010), because some turtles still could have had non-zero probabilities of heavy oiling. Although this issue certainly affected our analyses, no heavily oiled turtles were rescued from the northern GoM after August 1, and the vast majority of turtles rescued after August 11 were unoiled or in the lowest oiling categories (Figures 1 and 2; Stacy, 2012a). Therefore, we concluded that despite the temporally limited SAR data, our model approach to estimate probabilities of heavy oiling still accurately characterized the relative potential for heavy oil exposure throughout the spill period.

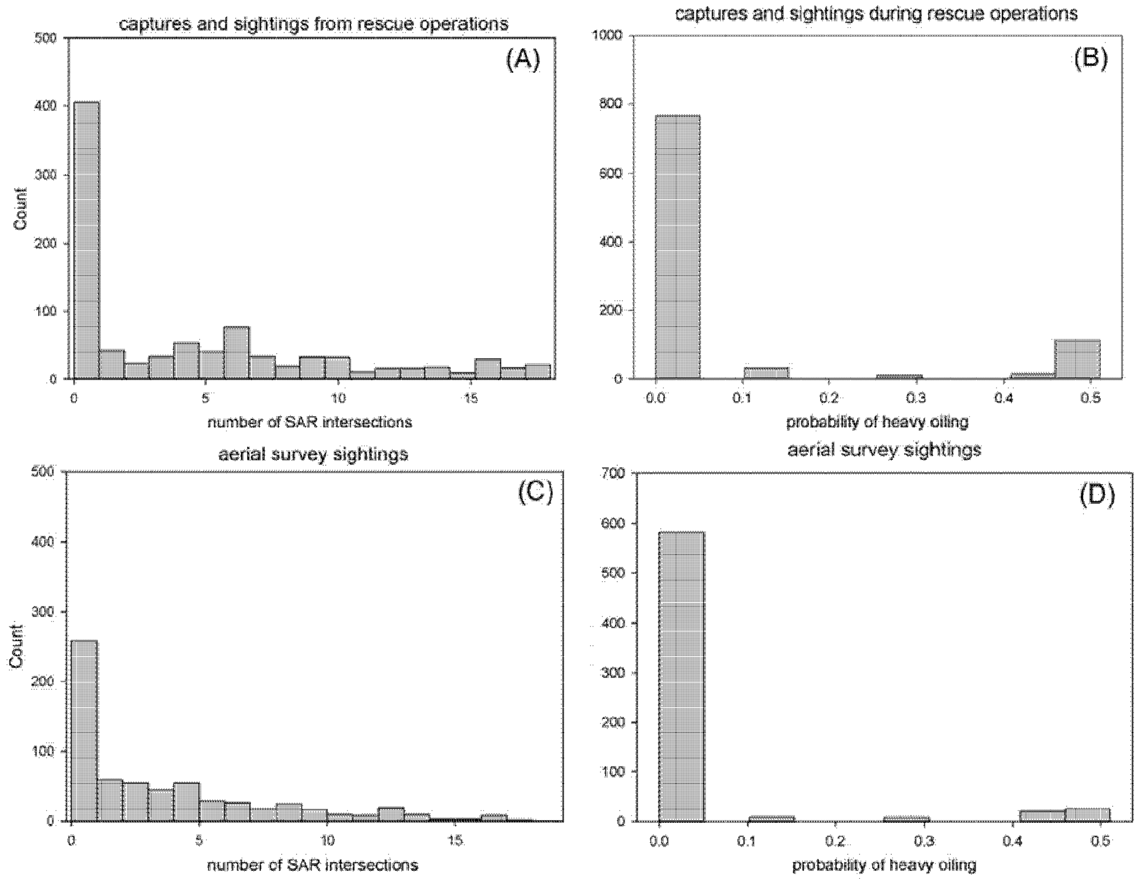

Figure 13. Number of SAR intersections (A and C) and probabilities of heavy oiling (B and D) for turtles documented during rescue operations (A and B) and aerial surveys (C and D).

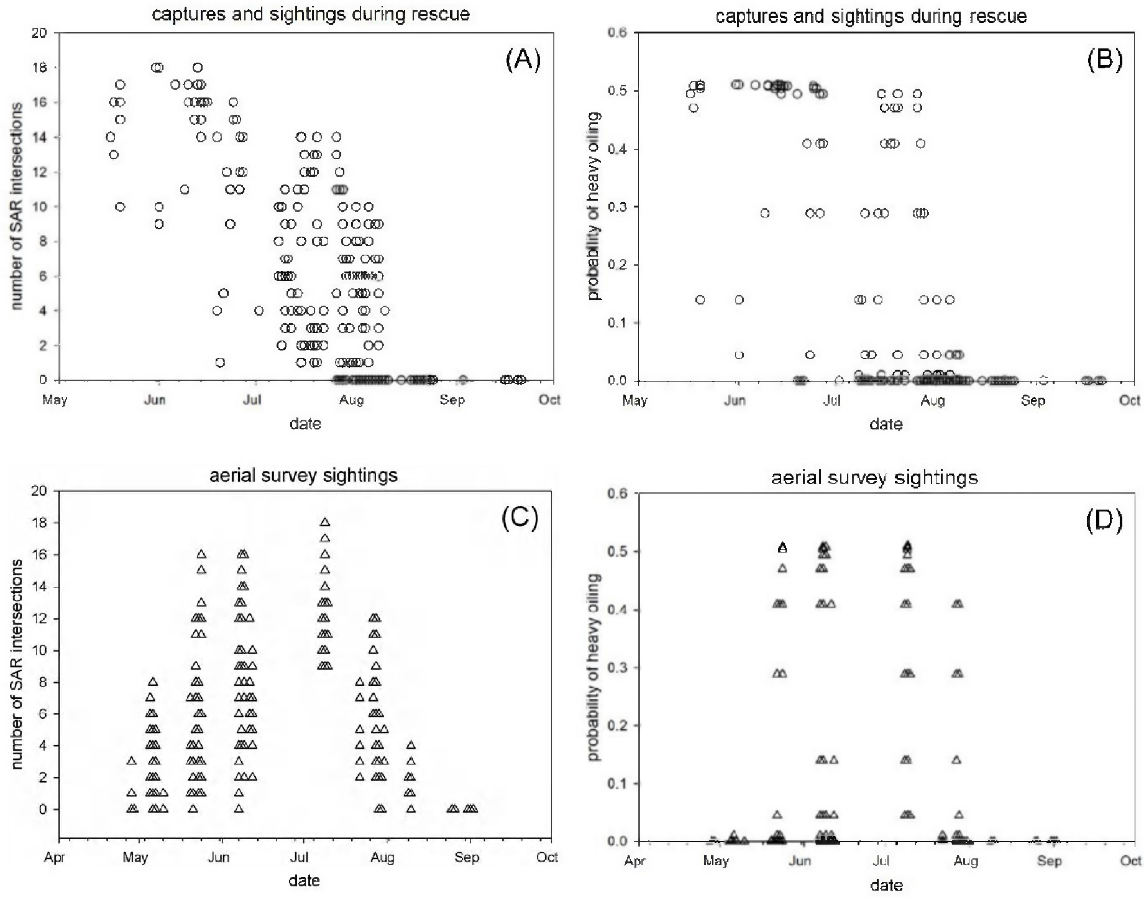

Figure 14. Number of SAR intersections (A and C) and probabilities of heavy oiling (B and D) for turtles documented during rescue operations (A and B) and aerial surveys (C and D); shown by date.

3.2 Probabilities of Heavy Oiling across the DWH Oil Footprint

To illustrate how potential exposure to heavy oiling changed in space and time at the scale of the entire DWH footprint, we generated daily maps of heavy oiling probabilities using the same binomial logistic regression approach that we used for estimated oiling categories for turtles. Average heavy oiling probabilities across all SAR days (April 23 to August 11, 2010) illustrated that the highest probability areas were centered around the wellhead, with decreasing probabilities extending in all directions within the footprint away from the wellhead (Figure 15). Although grey cells intersected with at least one daily SAR footprint and were included in the spatial extent of our analysis, these cells had so few intersections (< 4) that their associated probabilities of heavy oiling were essentially zero (< 0.000001).

We then overlaid locations and heavy oiling probabilities for all turtles captured or sighted during rescue operations (Figure 16) and those for turtles sighted during aerial surveys (Figure 17) on the average probability of exposure to heavy oil (Figure 15), estimated across the DWH oil footprint. (See animation of *daily probabilities of heavy oiling for all turtles observed across the cumulative SAR oil footprint:* https://dwh.nmfs.noaa.gov/TeamCollaborationSites/DARP/Injury%20Volume/4.8%20Sea%20Turtles/Workspace/probability_maps.wmv). As with the oiling probabilities across the DWH footprint, turtles with the highest probabilities of heavy oil exposure were limited to areas closest to the wellhead, and the probability of heavy oiling decreased with increasing distance from the wellhead (Figures 16 and 17). Although the entire area shown in Figures 15–17 had some intersections with the daily SAR footprint, and therefore some potential for oil exposure, we restricted the area within which oceanic turtle densities were calculated to those areas with > 0.01 probabilities of heavy oiling. This threshold corresponded to approximately seven SAR intersections within a 21-day period. Although it is possible that lethal sea turtle exposure to oil occurred in these areas, we restricted our analyses to the area that had the most persistent surface oil, and that consequently had higher probabilities of heavy oiling.

Although aerial surveys were restricted to water depths of < 200 m, and the survey area boundaries (Figure 4) were further westward than areas where rescue operations occurred (Figure 1), the resulting probabilities of heavily oiled turtles detected by plane-based observers showed a similar relationship. Given this broad agreement between empirical patterns of degree of oiling of turtles in oiled northern GoM habitats, and surface oil in space and time, we concluded that our modeling approach produced reasonable estimates of heavy oiling probability for turtles – and surface habitats – that were not directly observed during NRDA response and survey efforts.

3.3 Total Estimated Sea Turtle Injuries

3.3.1 Oceanic sea turtle injuries

The estimated density of all oceanic juvenile sea turtles within the DWH oil spill footprint (Figure 16) was 3.32 turtles per km^2 (heavily oiled turtles = 0.24 turtles per km^2, non-heavily oiled turtles = 3.08 turtles per km^2; McDonald et al., 2015). To quantify total injuries to small juvenile sea turtles, we combined these density estimates with areas within the oil footprint where turtles were expected to be, with non-zero probabilities of heavy oil exposure (Figure 16), and mortality estimates for heavily oiled and non-heavily-oiled turtles.

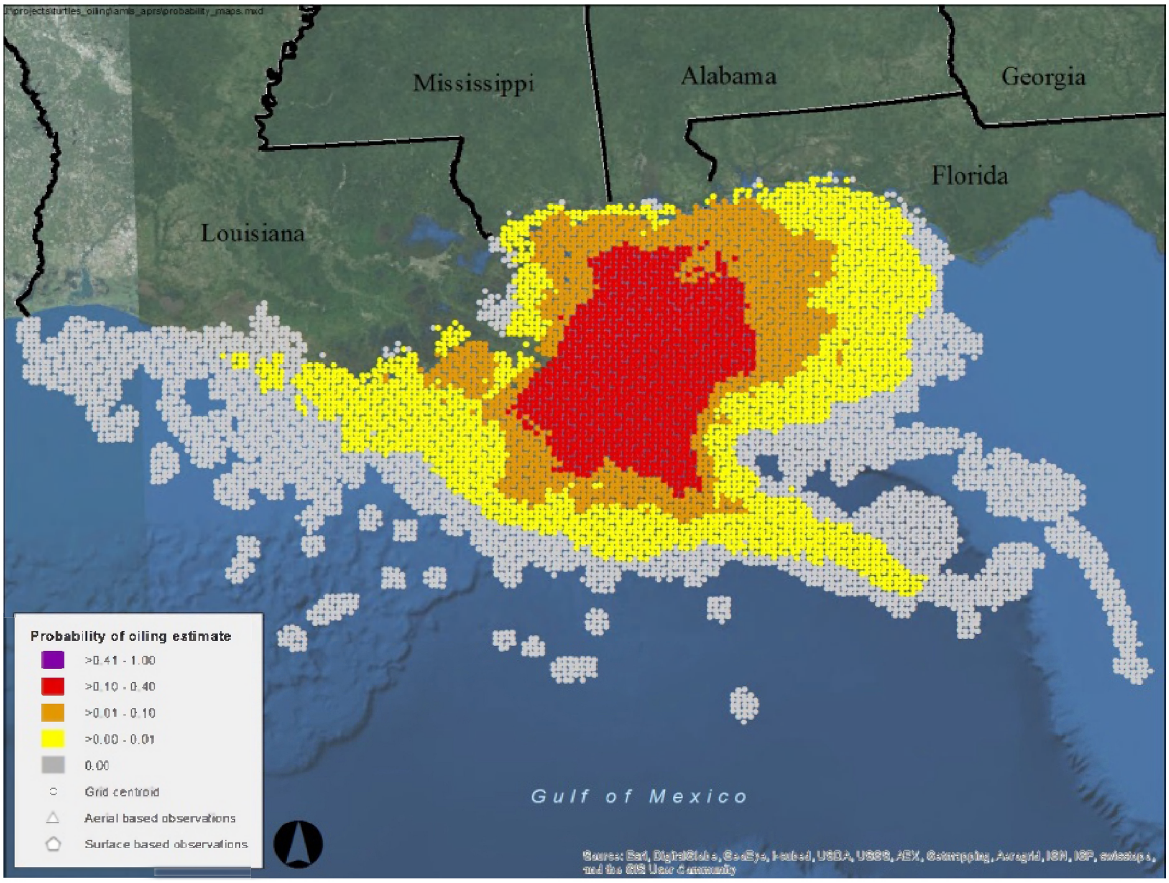

Figure 15. Mean probabilities of heavy oil exposure across the DWH oil spill zone and period. Values are mean probabilities calculated for the centroids of all 5 km x 5 km grid cells that intersected with the DWH oil footprint.

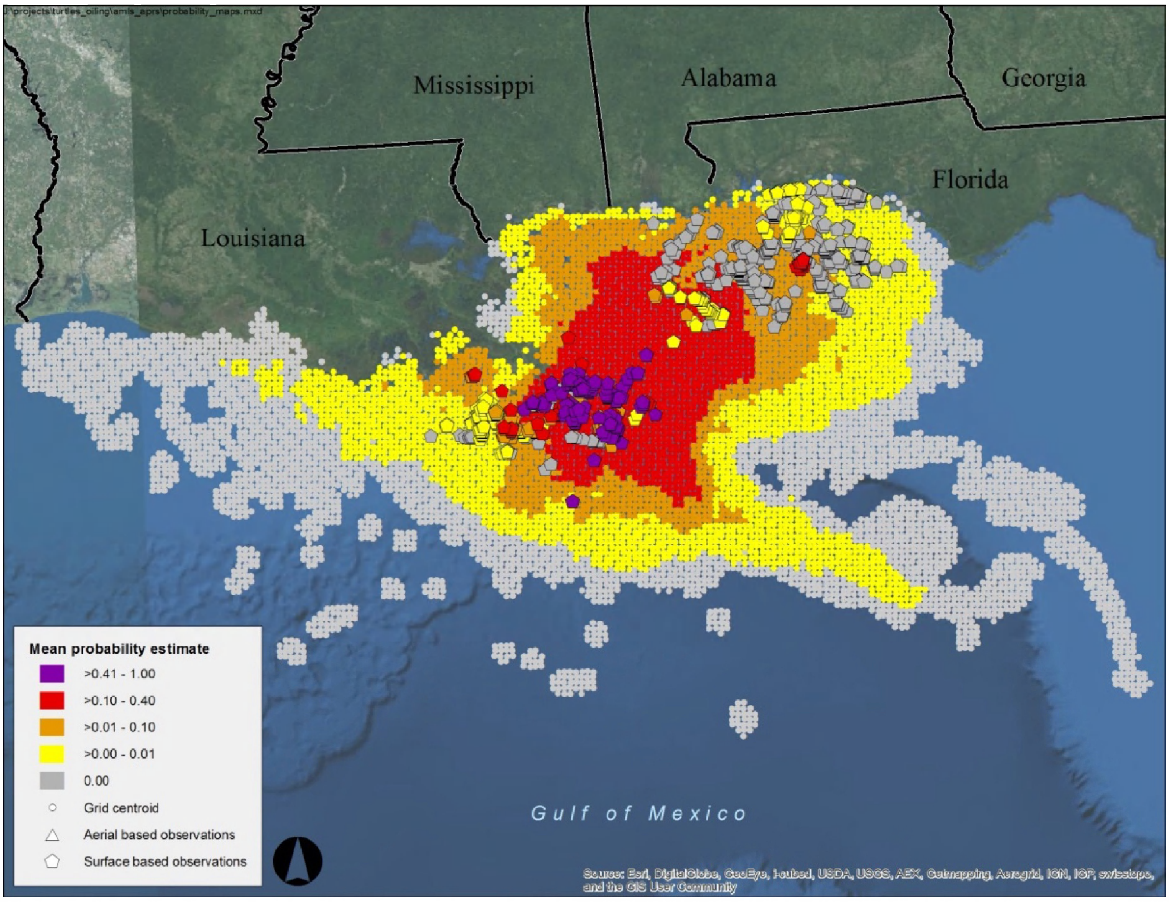

Figure 16. Probabilities of heavy oil exposure for oceanic (i.e., small juvenile) sea turtles across the DWH oil spill zone and period. Values are probabilities calculated for each turtle captured or sighted during boat-based rescue operations (see Section 2.1.1 for more details), and mean probabilities for the centroids of all 5 km x 5 km grid cells that intersected with the DWH oil footprint.

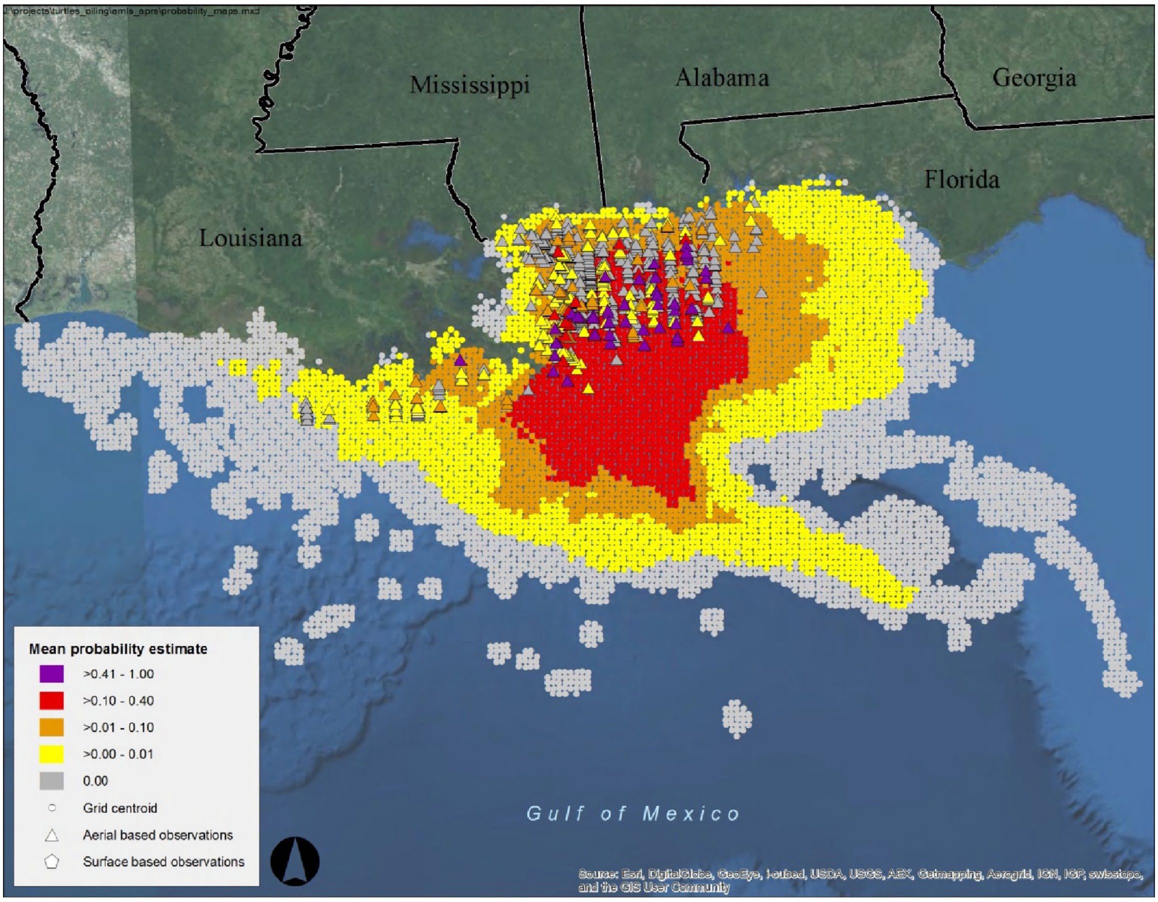

Figure 17. Probabilities of heavy oil exposure for neritic (i.e., large juvenile and adult) sea turtles across the DWH oil spill zone and period. Values are probabilities calculated for each turtle sighted during aerial surveys (see Section 2.1.2 for more details), and mean probabilities for the centroids of all 5 km x 5 km grid cells that intersected with the DWH oil footprint.

The Trustees estimated that more than 420,000 small juvenile sea turtles were exposed to DWH oil across more than 110,000 km^2 of the cumulative oil footprint (Table 3). After applying the mortality estimates presented in Section 2.1.1 to the numbers of turtles exposed in each oiling category, we estimated that approximately 56,000 small juvenile sea turtles were killed by heavy exposure to DWH oil. Accounting for toxicological and physiological adverse effects associated with less than heavy oil exposure, up to an additional 110,000 turtles were likely killed. Thus, as many as 166,000 oceanic juvenile sea turtles were likely killed by the DWH oil spill (Table 3).

Table 3. Densities, exposures, and estimated mortality of small juvenile sea turtles. The Trustees calculated the number of turtles that were heavily oiled, and thus assumed dead (100% mortality for heavily oiled turtles), and also calculated the number of turtles exposed to a lesser degree than heavily oiled turtles. To estimate total potential mortality for the latter group, the Trustees applied a mortality rate of 30%, which considered potential toxic effects of oil exposure and physiological derangements observed in rescued turtles (Mitchelmore et al., 2015; Stacy, 2012b). We considered the total number of heavily oiled dead neritic turtles to be the low end of the range of mortality, and the addition of the number of less-than-heavily oiled dead neritic turtles to be the high end of the range of total mortality. Exposure and injury estimates are shown to three significant digits.

Species	Density (turtles/km^2)	Total turtles exposed	Heavily oiled, dead (low end of the range)	Non-heavily oiled, dead	Total dead (high end of the range)
Kemp's ridleys	1.70	217,000	36,200	54,100	90,300
Loggerheads	0.25	30,800	2,140	8,590	10,700
Greens	1.22	154,000	15,700	41,600	57,300
Hawksbills	0.07	8,850	615	2,470	3,090
Unidentified	0.08	10,700	1,360	2,800	4,160
Total	**3.32**	**421,000**	**56,000**	**110,000**	**166,000**

Note: Totals may not sum because of rounding.

3.3.2 Neritic sea turtle injuries

We combined estimates of turtle density and abundance in the survey area oil within the DWH footprint (Garrison, 2015) with probabilities of heavy oil exposure (Figure 17), and associated mortality estimates to quantify total injuries to large juvenile and adult sea turtles in continental shelf areas. Based on these calculations, more than 58,000 neritic sea turtles were exposed to DWH oil in continental shelf areas (Garrison, 2015) (Table 4). These estimates also included a size class of young Kemp's ridley juveniles – approximately 25–40 cm long and approximately 3 years old (Avens and Snover, 2013) – that were unobservable by boat-based and plane-based surveys of the DWH spill area because they would not have been in areas targeted by rescue efforts and they would not have been visible from aircraft because of their small size (Garrison, 2015). Because the actual distribution of these animals is relatively poorly known, Garrison (2015) estimated their abundance relative to the estimated abundance of all other continental shelf Kemp's ridleys, and assumed that they were uniformly distributed and exposed to oil in similar proportions to turtles that were sighted. This allowed for estimates of the potential number of these small, continental shelf juveniles that were exposed to and killed by the DWH oil spill (Table 4, Kemp's ridleys age 3).

Table 4. Total exposures and estimated mortality of neritic (i.e., large juvenile and adult) sea turtles killed by the DWH oil spill in continental shelf areas. We considered the total number of heavily oiled dead neritic turtles to be the low end of the range of mortality, and the addition of the number of less-than-heavily oiled dead neritic turtles to be the high end of the range of total mortality. Numbers shown to two significant digits.

Species	Total exposures	Heavily oiled, dead (low end of the range)	Non-heavily oiled exposures	Non-heavily oiled, dead	Total dead (high end of the range)
Kemp's ridleys, ages 4 +	21,000	1,700	19,000	950	2,700
Kemp's ridleys, age 3	990	380	610	30	410
Kemp's, all	*22,000*	*2,100*	*20,000*	*980*	*3,100*
Loggerheads	30,000	2,200	28,000	1,400	3,600
Unidentified	5,900	630	5,200	260	890
Total	**58,000**	**4,900**	**53,000**	**2,600**	**7,600**

Note: totals may not sum due to rounding.

After applying the mortality estimates for neritic turtles described in Section 2.1.2 to the numbers of turtles exposed in the heavy oiling and non-heavy oiling exposure categories, we estimated that the DWH spill killed between 4,900 and 7,600 large juvenile and adult turtles in continental shelf areas (Table 4).

3.3.3 Uncertainties associated with quantification of injuries to sea turtles

There are uncertainties associated with these estimates, as indicated by the wide range of possible injuries to sea turtles in both life stages. Sources of uncertainty in the mortality estimates, particularly those for non-heavily-oiled turtles, included several factors that were not empirically observed in sea turtles, such as chronic toxic effects on critical physiological functions (Mitchelmore et al., 2015). These uncertainties could have either underestimated or overestimated mortality, as well as the resulting injury quantification.

A factor that might have resulted in overestimate of small juvenile sea turtle injuries was the potential overestimation of the total area where turtles might have been exposed. We assumed that turtles anywhere in the DWH oil footprint that had a non-zero probability of heavy oil exposure were exposed to oil, but convergence zones that aggregate surface habitat and oceanic sea turtles are patchily distributed and ephemeral (Hu, 2015). It is possible that the exposure areas that we used overestimated the total area of actual sea turtle habitat. Although it would have been preferable to multiply turtle densities by the area of actual turtle habitat, such estimates were not available.

Another source of potential overestimation was in mortality estimates applied to different life stages and oiling categories. Mortality estimates for large juveniles and adults were developed based on strong empirical evidence about physical effects of exposure to surface oil observed in small juvenile sea turtles (Stacy, 2012a; Mitchelmore et al., 2015; Section 2.1.1, this report); empirical observations of oiled neritic sea turtles were scarce. Sufficient information was not available to more finely resolve size-related differences in distribution; these differences could have been meaningful to incorporate into mortality estimates.

However, other sources of uncertainty could have made the injury numbers presented in Tables 3 and 4 underestimates. Specifically, several factors hindered searchers' ability to detect turtles. For example, turtles mired in oil were harder to see, and dead turtles also probably sank quickly and were thus not detected (McDonald et al., 2015). Additionally, the survey efforts covered less than 10% of the cumulative oil footprint and did not occur uniformly through time. Despite these uncertainties, we concluded that these injury estimates were reasonable and that they adequately quantified the magnitude of the injury to sea turtles because they were based on the best available information and were quantified using sound technical approaches.

4. Conclusions and Implications for Future Wildlife Injury Assessments in Marine Oil Spills

In marine oil spills, systematic documentation of the presence and distribution of wildlife relative to oil, as well as wildlife health status, exposures to oil, and adverse effects of those exposures is extremely challenging (Stacy, 2012a). The probability model approach that we developed for assessing injuries to turtles in the wake of the DWH spill provided a measure of the proximity and persistence of surface oil. Our approach was a simple yet informative proxy for relative probability of oil exposure for turtles in a certain area at a certain time. Furthermore, it allowed the Trustees to expand the injury quantification from sea turtles and oil exposures that were directly observed in the field to a more holistic quantification of the full extent and magnitude of potential sea turtle injuries. The population-level context for our injury estimates is presented in the PDARP Injury Chapter: Sea Turtle Injury Assessment section.

In our present example of turtles exposed to DWH oil, we developed an approach to estimate the probability of heavy oiling for turtles and areas within the cumulative DWH footprint whose oiling status was not observed directly (Garrison, 2015; McDonald et al., 2015). Additionally, we adapted the approach to expand the overall areas to which turtle density estimates could be applied to estimate total abundance, exposures to oil, and mortality (McDonald et al., 2015). Our approach offered several important advantages for estimating exposures of wildlife – including, but not limited, to sea turtles – to surface oil. First, it combined ubiquitous, reliable data (i.e., satellite-derived measurements of surface oil and empirical observations of the extent of oiling on sea turtles) to statistically estimate the probability of heavy oil exposure in cases where the former data type was available, but not the latter. Second, it could be adapted to various situations in which the scale of the potential oil exposures exceeded the scale of the available documentation of oil exposures.

Assessment of oil exposures and their effects on marine wildlife require novel approaches for collecting direct observational data in the field and for expanding on these observations to produce estimates at scales that match the full nature and magnitude of the spill. The oiling probability modeling tool that we have described here was one such approach that allowed the Trustees to leverage field-collected information about the degree of oil exposure and construct a modeling framework that described general relationships among turtles, degree of oiling, and surface oil. This approach expanded exposure and injury quantification to areas and animals that were not directly evaluated, but were nonetheless exposed to oil and to its associated adverse effects. For these reasons, we encourage application of this approach to estimate oil exposures in future marine oil spills, particularly those that primarily affected areas distant from land, in offshore areas.

Literature Cited

Avens, L. and M.L. Snover. 2013. Age and age estimation in sea turtles. In *Biology of Sea Turtles, Vol. III*, J.A. Musick, J. Wyneken, and K.J. Lohmann (eds.). CRC Press, Boca Raton, FL. pp. 97–134.

Avens, L., L.R. Goshe, L. Coggins, M.L. Snover, M. Pajuelo, K.A. Bjorndal, and A.B. Bolten. 2015. Age and size at maturation and adult-stage duration for loggerhead sea turtles in the western North Atlantic. *Marine Biology*. doi: 10.1007/s00227-015-2705-x.

Bolten, A.B. 2003. Variation in sea turtle life history patterns: Neritic vs. oceanic life history stages. Chapter 9 in *The Biology of Sea Turtles Vol. II*, P.L. Lutz, J.A. Musick, and J. Wyneken (eds.). CRC Press, Boca Raton, FL.

Brown-Peterson, N.J., M. Krasnec, R. Takeshita, C.N. Ryan, K.J. Griffitt, C. Lay, G.D. Mayer, K.M. Bayha, W.E. Hawkins, I. Lipton, J. Morris, and R.J. Griffitt. 2015. A multiple endpoint analysis of the effects of chronic exposure to sediment contaminated with *Deepwater Horizon* oil on juvenile Southern flounder and their associated microbiomes. *Aquat Toxicol* 165:197–209. doi: 10.1016/j.aquatox.2015.06.001.

Camacho, M., P. Calabuig, O.P. Luzardo, L.D. Boada, M. Zumbado, and J. Orós. 2013. Crude oil as a stranding cause among loggerhead sea turtles (*Caretta caretta*) in the Canary Islands, Spain (1998–2011). *Journal of Wildlife Diseases* 49:637–640.

Drake, D.L. and J.R. Spotila. 2002. Thermal tolerances and the timing of sea turtle hatchling emergence. *Journal of Thermal Biology* 27:71–81. doi: 10.1016/S0306-4565(01)00017-1.

Garcia-Pineda, O., B. Zimmer, M. Howard, W. Pichel, X. Li, and I. MacDonald. 2009. Using SAR images to delineate ocean slicks with a texture-classifying neural network algorithm (TCNNA). *Can J Remote Sensing* 35:1–11.

Garrison, L. 2015. Estimated Lethal and Sub-Lethal Injuries of Sea Turtles on the Continental Shelf in the Northern Gulf of Mexico Based on Aerial Survey Abundance Estimates and Surface Oiling. Technical Report Prepared for: NOAA Assessment and Restoration Division.

Graettinger, G., J. Holmes, O. Garcia-Pineda, M. Hess, C. Hu, I. Leifer, I. MacDonald, F. Muller-Karger, J. Svejkovsky, and G. Swayze, 2015. Integrating Data from Multiple Satellite Sensors to Estimate Daily Oiling in the Northern Gulf of Mexico during the *Deepwater Horizon* Oil Spill. NOAA Technical Report. Seattle: U.S. Department of Commerce.

Hart, K.M., M.M. Lamont, A.R. Sartain, and I. Fujisaki. 2014. Migration, foraging, and residency patterns for northern Gulf loggerheads: Implications of local threats and international movements. *PLoS ONE* 9(7):e103453. doi: 10.1371/journal.pone.0103453.

Helm, R.C., D.P. Costa, T.D. DeBruyn, T.J. O'Shea, R.S. Wells, and T.M. Williams. 2015. Overview of effects of oil spills on marine mammals. In *Handbook of Oil Spill Science and Technology,* 1st edition, M. Fingas (ed.). John Wiley & Sons, Inc. pp. 455–475.

Hochscheid, S. 2014. Why we mind sea turtles' underwater business: A review on the study of diving behavior. *Journal of Experimental Marine Biology & Ecology* 450:118–136.

Hu, C. 2015. *Sargassum* Injury Assessment Plan: Mapping Using Remote Sensing. Draft Technical Report. Prepared for: NOAA Assessment and Restoration Division.

Jessop, T.S., M. Hamann, M.A. Read, and C.J. Limpus. 2000. Evidence for a hormonal tactic maximizing green turtle reproduction in response to a pervasive ecological stressor. *General and Comparative Endocrinology* 118:407–417.

Lamont, M.M., N. Putman, I. Fujisaki, and K. Hart. 2015. Spatial requirements of different life-stages of the loggerhead turtle (*Caretta caretta*) from a distinct population segment in the northern Gulf of Mexico. *Herpetological Conservation and Biology* 10: 26–43.

Leighton, F.A. 1993. The toxicity of petroleum oils to birds. *Environmental Review* 1:92–103.

Lemon, S.C., J. Roy, M.A. Clark, P.D. Friedman, and W. Rakowski. 2003. Classification and regression tree analysis in public health: Methodological review and comparison with logistic regression. *Ann Behav Medicine* 26:172–181.

Mansfield, K.L., J. Wyneken, W.P. Porter, and J. Luo. 2014. Satellite tracks of neonate sea turtles redefine the 'lost years' oceanic niche. *Proceedings of the Royal Society B: Biological Sciences* 281:20133039. Available: http://dx.doi.org/10.1098/rspb.2013.3039.

McDonald, T., B. Witherington, B. Schroeder, and B. Stacy. 2015. Estimates of Surface-Pelagic (Oceanic) Juvenile Sea Turtles Oiled by MC 252 Spill.

Mitchelmore, C., C.T. Bishop, and T.K. Collier. 2015. Estimated Mortality of Oceanic Sea Turtles Oiled during the BP *Deepwater Horizon* Oil Spill. Technical Report Prepared for: NOAA Assessment and Restoration Division.

Munilla, I., J.M. Arcos, D. Oro, D. Alvarez, P.M. Leyenda, and A. Velando. 2011. Mass mortality of seabirds in the aftermath of the *Prestige* oil spill. *Ecosphere* 2(7):art83. Available: http://dx.doi.org/10.1890/ES11-00020.1.

pDARP Injury Chapter, Natural Resource Exposure Assessment section.

pDARP Injury Chapter, Sea Turtle Injury Assessment section.

Peterson, C.H., S.D. Rice, J.W. Short, D. Esler, J.L. Bodkin, B.E. Ballachey, and D.B. Irons. 2003. Long-term ecosystem response to the *Exxon Valdez* oil spill. *Science* 302(5653):2082–2086.

Piatt, J.F. and R.G. Ford. 1996. How many seabirds were killed by the *Exxon Valdez* oil spill? In *Proceedings of the Exxon Valdez Oil Spill Symposium, 2–5 February 1993, Anchorage, AK*, S.D. Rice, R.B. Spies, D.A. Wolfe, and B.A. Wright (eds.). American Fisheries Society, Bethesda, MD. pp. 712–719.

Putman, N.F. and K.L. Mansfield. 2015. Direct evidence of swimming demonstrates active dispersal in the sea turtles "lost years." *Current Biology* 25:1–7.

Schwacke, L.H., C.R. Smith, F.I. Townsend, R.S. Wells, L.B. Hart, B.C. Balmer, T.K. Collier, S. De Guise, M.M. Fry, L.J. Guillette Jr., S.V. Lamb, S.M. Lane, W.E. McFee, N.J. Place, M.C. Tumlin, G.M. Ylitalo, E.S. Zolman, and T.K. Rowles. 2014. Health of common bottlenose dolphins (*Tursiops truncatus*) in Barataria Bay, Louisiana, following the *Deepwater Horizon* oil spill. *Environmental Science & Technology* 48(1):93–103.

Shaver, D.J., K.M. Hart, I. Fujisaki, C. Rubio, A.R. Sartain, J. Pena, P.M. Burchfield, D. Gomez Gamez, and J. Ortiz. 2013. Foraging area fidelity for Kemp's ridleys in the Gulf of Mexico. *Ecology and Evolution* 3(7):2002–2012.

Shigenaka, G. 2003. Oils and sea turtle: Biology, planning, and response. Office of Response and Restoration, NOAA Ocean Service, Seattle, WA.

Southwood Willard, A. 2013. Physiology as integrated systems. In *Biology of Sea Turtles, Vol. III*, J.A. Musick, J. Wyneken, and K.J. Lohmann (eds.). CRC Press, Boca Raton, FL. pp. 1–30.

Stacy, B. 2012a. Summary of Findings for Sea Turtles Documented by Directed Captures, Stranding Response, and Incidental Captures under Response Operations during the BP DWH MC252 Oil Spill.

Stacy, N.I. 2012b. Analysis and Interpretation of Hematology and Blood Chemistry Values in Live Sea Turtles Documented by Response Operations during the 2010 BP *Deepwater Horizon* Oil Spill Response.

Stout, S.A. 2014. Chemical Fingerprinting of Sea Turtle Wipe Samples from the Northern Gulf of Mexico during and after the *Deepwater Horizon* Oil Spill.

Vander Zanden, H.B., A.D. Tucker, K.M. Hart, M.M. Lamont, I. Fujisaki, D.S. Addison, K.L. Mansfield, K.F. Phillips, M.B. Wunder, G.J. Bowen, M. Pajuelo, A.B. Bolten, and K.A. Bjorndal. 2015. Determining origin in a migratory marine vertebrate: A novel method to integrate stable isotopes and satellite tracking. *Ecological Applications* 25:320–335.

Wallace, B.P., A.D. DiMatteo, A.B. Bolten, M.Y. Chaloupka, B.J. Hutchinson, F.A. Abreu-Grobois, J.A. Mortimer, J.A. Seminoff, D. Amorocho, K.A. Bjorndal, J. Bourjea, B.W. Bowen, R. Briseño-Dueñas, P. Casale, B.C. Choudhury, A. Costa, P.H. Dutton, A. Fallabrino, E.M. Finkbeiner, A. Girard, M. Girondot, M. Hamann, B.J. Hurley, M. López-Mendilaharsu, M.A. Marcovaldi, J.A. Musick, R. Nel, N.J. Pilcher, S. Troëng, B. Witherington, and R.B. Mast. 2011. Global conservation priorities for marine turtles. *PLoS ONE* 6(9):e24510. doi: 10.1371/journal.pone.0024510.

Witherington, B., S. Hirama, and R. Hardy. 2012. Young sea turtles of the pelagic *Sargassum*-dominated drift community: Habitat use, population density, and threats. *Marine Ecology Progress Series* 463:1–22.

Ylitalo, G., T. Collier, and B. Stacy. 2014. Sea Turtle Exposure to MC252 Oil and Dispersants in the Northern Gulf of Mexico during and Following the *Deepwater Horizon* Spill: Results of Chemical Analyses of Tissues, Bile and Gastroenteric Contents from Necropsied Sea Turtles.