Evaluating Prevalence and Mortality of External Injuries on Loggerhead (*Caretta caretta*) and Green (*Chelonia mydas*) Sea Turtles in Florida, USA

by

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DEDICATION

I dedicate this thesis to my boyfriend, Dominic; my sister, Allison; and my mom; Kinga. Thank you for your never-ending support and love that has helped me achieve my dreams.

I would also like to thank my friends who have encouraged and supported me throughout this entire process: Andie, Michael, Alex, Heather, Kara, Alexa, and Nick. Thank you for reading through drafts, talking me through meltdowns, and encouraging me to continue working hard to reach my goals. Finally, I would like to thank my dad, Tom, who instilled within me from a young age that science was important and learning was cool.

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ABSTRACT

Anthropogenic threats, such as bycatch, boat strikes, and pollution, account for two to three times more sea turtle mortality events than natural causes. The goals of this study were to: (1) determine prevalence and cause of external traumatic injuries on nesting loggerhead sea turtles (*Caretta caretta*) in Juno Beach, Florida and (2) conduct an analysis of historical rehabilitation data from Florida Fish and Wildlife Conservation Commission (FWC) to calculate mortality of loggerhead and green (*Chelonia mydas*) turtles injured by boats. During the 2019 nesting season, 300 loggerheads were tagged and examined for external injuries. All injuries were categorized based on type, condition, and anatomic location. Red light photos from the field and FWC stranding data were analyzed using ImageJ. Case outcome (e.g., died, euthanized, released) and mortality (e.g., died, survived) of turtles entering rehabilitation facilities were analyzed separately. To test for differences in injury prevalence of nesting loggerheads and for differences in the case outcome of rehabilitation patients' contingency tables were created. To test the association between numeric independent variables (e.g., SCL_{min}, injury size, number of injuries, and number of injury locations) and mortality, a multiple logistic regression was run. Contingency tables were created to test for differences in mortality according to all other variables. Approximately 24% (N=71) of tagged nesting loggerheads had an external injury. The majority of the identifiable injuries were boat strikes (68%), followed by shark interactions (18%), hook injuries (9%), and entanglements (5%). Additionally, for each unit increase in the number of injured anatomic locations, the odds of the turtle dying during rehabilitation increased by a factor of 5.99 in loggerheads. Green turtles entering rehabilitation facilities had significant differences in case outcome depending on injury area, width, lateral carapace presence, condition, and severity. Injury width and injury severity were significantly related to mortality in green turtles. For each unit increase in average injury width to straight carapace width (SCW) ratio the odds of a green turtle dying in rehabilitation increased by a factor of 217.02. Healed injuries had a significantly lower probability of mortality, when compared with fresh and partially healed injuries in both loggerheads and green turtles. The results of this study provide new insight into the impact that anthropogenic and natural threats have on sea turtles, as the nesting females in this study survived these interactions without veterinary intervention. The results can be used to create/improve upon conservation management plans, such as boat speed restriction zones, and rehabilitation facility triage decisions.

INTRODUCTION

Sea turtles are subject to many anthropogenic threats including fisheries bycatch, harvest of eggs and live turtles, coastal development, pollution/plastic ingestion, climate change, and boat interactions (Wallace et al., 2011). These threats are thought to account for two to three times more sea turtle deaths than those resulting from natural causes (Casale et al., 2010); however, a number of these threats remain largely unquantified (Bolten et al., 2011). It is important to identify risks and the extent to which these threats are impacting our wildlife, especially for large, migratory species, like sea turtles, in order to better protect them by implementing better management plans (Hazel & Gyuriz, 2006).

ENTANGLEMENT/HOOK

Entanglement and hook wounds result from direct interactions with fisheries or free-floating fishing line/net that has been lost or discarded (i.e., ghost gear; Wallace et al., 2010; Hamelin et al., 2016; Duncan et al., 2017). Entanglement is one of the leading causes of mortality in marine megafauna, including sea turtles (Knowlton & Kraus, 2001; Robbins & Mattila, 2004; Chaloupka et al., 2008; Knowlton et al., 2012). When turtles directly interact with fisheries, they usually end up as bycatch, and as such they either drown, are released with minimal-to-moderate-trauma, or are released with severe injuries that later result in death (Knowlton & Kraus, 2001; Lewison et al., 2004; Peckham et al., 2008; Murray, 2015). It is estimated that 17–42% of loggerhead sea turtles (*Caretta caretta*) that interact with longline gear die from these interactions

(Lewison et al., 2004). Even if death is not immediate, these interactions can affect health (e.g., infection, muscle necrosis) and biology (e.g., feeding, locomotion, reproduction) of turtles, which may ultimately result in mortality or have population level effects (without directly resulting in mortality) (Moberg, 1985; Innis et al., 2010; Hamelin et al., 2016).

Hook wounds often occur due to foraging behavior around pelagic longlines or piers, whereby sea turtles attempt to consume bait on the hook (Lewison et al., 2004; Watson et al., 2005). This can lead to ingestion of the hook or external hook-related injuries (Watson et al., 2005). Similarly, entanglements more frequently occur anteriorly around the neck or front flippers and any unsuccessful attempts by the turtle to remove the gear can result in further entrapment (Hamelin et al., 2016). In Florida, USA, an estimated 3.7% of sea turtle strandings are due to hook and line interactions or some other form of entanglement (only 0.5% from non-fishing gear) (Foley et al., 2017). Stranding data likely underestimate fishing gear-related turtle mortality due to the absence of scars on dead, stranded turtles, and due to the inability to account for scarring when carcasses are in advanced stages of decomposition (Peckham et al., 2008; Mancini & Koch, 2009).

Research on gear usage, temporal and spatial distribution of fisheries, and turtle interactions, aid in a better understanding of how to limit the number of turtles affected by fisheries (Watson et al., 2005; Moore et al., 2010; Wallace et al., 2010; Murray, 2015). The use of turtle exclusion devices (TEDs) allows sea turtles to better escape when trapped in a shrimp trawl net; however, they do not decrease the amount of interactions turtles have with the gear (Murray, 2015). Furthermore, sea turtles that interact with TEDs may not have a 100% survival rate due to becoming forcibly submerged in the trawls (leading to an inability to surface to breathe), colliding with gear, and stress from the interaction (Innis et al., 2010; Gilman et al., 2013). Hook design and bait type have also been investigated with the goal of reducing sea turtle mortality with pelagic longlines (Watson et al., 2005). For example, loggerhead bycatch decreased by 90% when using a circle hook with mackerel bait compared to J hooks and squid bait (Watson et al., 2005). Spatial hotspots (i.e. high intensity) for turtle bycatch have been identified in the southwest Atlantic Ocean, eastern Pacific Ocean, and Mediterranean Sea (Lewison et al., 2014). Understanding when and where turtles are most likely to interact with gear is important for reducing fisheries mortality either via bycatch or entanglement.

BOAT STRIKES

Boats pose another major threat to a variety of aquatic organisms through direct and indirect interactions. Direct boat collisions impact manatees, cetaceans, and marine and freshwater turtles, resulting in propeller injuries or blunt force trauma (Laist & Shaw, 2006; Vanderlaan & Taggart, 2007; Heinrich et al., 2012; Dwyer et al., 2013; Foley et al., 2017). Even small fishes and fish larvae can be impacted by boat propellers (Killgore et al., 2001; Killgore et al., 2011). Boat strikes account for ~100–1,000 sea turtle deaths in the northwest Atlantic subpopulation annually (Bolten et al., 2011), and ~6–16% of sea turtle stranding and mortality around the globe, although data are scarce or lacking for many geographic regions (Kopsida at al., 2002, Hazel & Gyuriz, 2006, Tomas et al., 2008, Casale et al., 2010; Orós et al., 2016). In Florida, USA, sea turtle strandings associated with boat strikes increased from 10% to 30% between 1985 and 2005 (Singel et al., 2007). After disease, boat strikes are the second leading cause of stranding (Foley et al., 2017). Boat-related strandings account for ~43% of sea turtle strandings in Palm

Beach County, Florida, USA, alone, where there is higher boat traffic than other areas of Florida (Singel et al., 2007; Foley et al., 2017). Strandings from boat strikes tend to increase in spring and summer months, as sea turtles migrate into warmer, near-shore, and therefore boater-friendly areas for foraging and mating (Kopsida et al., 2002, Casale et al., 2010).

This high rate of boat-based interactions is likely due to concomitant increases in boat traffic, boat registration, and sea turtle populations. In 2010, Florida, USA, had 914,535 boat registrations, the highest recorded in the United States for that year (National Marine Manufacturers Association, 2011). A positive correlation exists between the location of marinas, navigable waterways, and inlets, and the number of boat-related sea turtle strandings in those locations (Foley et al., 2017). When identifying cause of death in stranded turtles, scientists tend to be conservative due to uncertainties regarding visual characteristics of the injuries. Therefore, some boat-related injuries might be reported as "unknown causes," resulting in boat-interaction numbers that are likely lower than what is actually occurring (Foley et al., 2017).

Sea turtle mortality from boat collisions usually occurs due to blunt-force trauma or from injuries caused by the propeller when a turtle is unable to avoid an approaching boat (Heinrich et al., 2012). Generally, sea turtles are not able to avoid being hit by boats at speeds higher than 4km/h (2.5 mph); most boat traffic greatly exceeds this speed (Hazel et al., 2007). Speed also plays a role in the degree of damage done to a turtle in a collision, with faster speeds inflicting more damage (Work et al., 2010). In shallow coastal waters, the threat of boat strikes to sea turtles is particularly high (Shimada et al., 2017). Hazel et al. (2007), found that higher speeds increased the chances of collision with green turtles (*Chelonia mydas*) in Australia (Hazel et al., 2007). In sea turtle rehabilitation facilities, euthanasia and unassisted mortality percentages are highest in boat strike patients compared to other causes (e.g., entanglement, hook/monofilament lines, infectious disease, crude oil exposure) (Orós et al., 2016). In turtles admitted as patients at Loggerhead Marinelife Center (LMC), a sea turtle rehabilitation facility in Palm Beach County, Florida, USA, over a 10-year-period (2008–2018), ~14–20% had boat-related injuries and ~20–25% of those survived to be released (LMC, unpublished data; Fig. 1). Sea turtles with cranial trauma had 0% survival, while turtles with both cranial and carapacial damage had ~29% survival rate (LMC, unpublished data; Fig. 1); turtles with damage limited to the carapace had ~26% survival rate (LMC, unpublished data; Fig. 1). It is not clear why turtles impacted in multiple anatomic regions do not have lower survivability. Low sample size may play a role in this observation, given that there were <10 turtles per group with injuries to the carapace along with any other region of the body (e.g., head and carapace damage: $N = 9$). It is also possible that a turtle struck on the carapace would have already begun to dive down to avoid further collision with the propeller, but was unable to avoid some minor damage to the head. This scenario may have increased survivability when compared to a turtle that was first struck on the head, resulting in a more severe, deeper injury. Injuries to the lateral carapace and resulting extremities (i.e., flippers) resulted in higher survival rates (50% survival) compared with turtles struck on the carapace alone (26% survival; LMC, unpublished data; Fig. 1). Therefore, it is hypothesized that injury location influences mortality, as lateral boat strikes often impact the lungs, whereas medial strikes might impact the spinal cord (Wyneken, 2001).

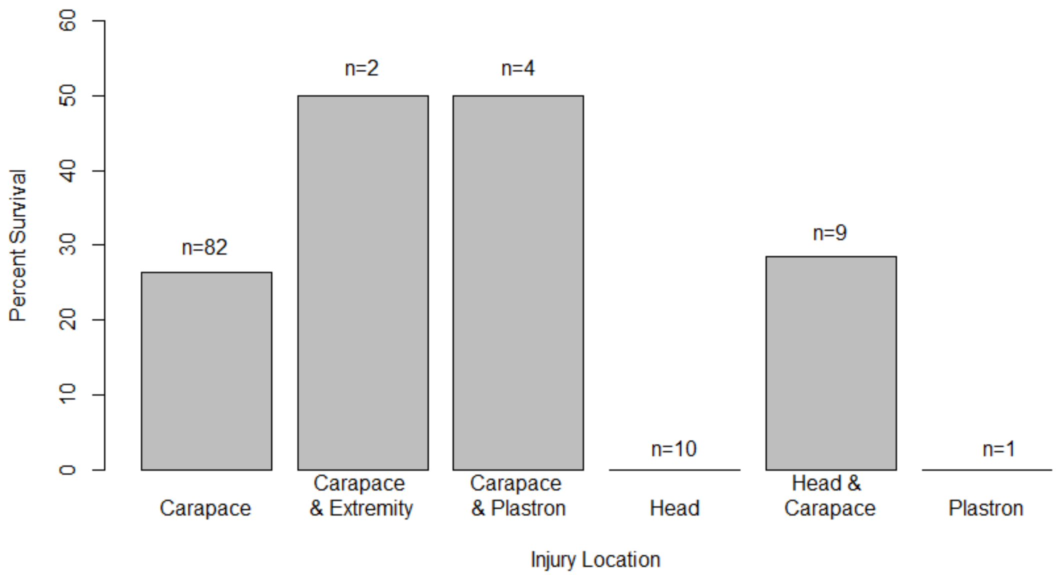

Figure 1. Survivorship of sea turtle patients with boat-related injuries admitted to Loggerhead Marinelife Center's Sea Turtle Hospital from 2008–2018. Percent survivorship was calculated according to the location of the injury (*N* = 96).

A number of protections have been enacted to reduce boat-related injury and mortality to marine life. Propeller guards are used by some boaters to protect wildlife; however, they are only effective in preventing propeller damage to the carapace of sea turtles at idle speeds and are not mandatory in most places (Work et al., 2010). Additionally, outboard jet motors are more successful at preventing damage to a sea turtle's carapace compared to propeller guards (Work et al., 2010). Implementation and enforcement of safe-boating initiatives, including boat speed restriction zones, are necessary in order to mitigate boat strike mortality in sea turtles (Hazel et al., 2007; Denkinger et al., 2013). Boat speed restrictions have been effective for Florida manatees (*Trichechus manatus latirostris*) and North Atlantic right whales (*Eubalaena glacialias*), for which well-designed and enforced mandatory speed zones have led to reduced mortality due to boat strikes in some geographic areas (Laist & Shaw, 2006; Vanderlaan & Taggart, 2007; Martin et al., 2016).

Sea turtles, therefore, face many anthropogenic risks, but certain natural threats (often influenced by anthropogenic factors) also impact sea turtle health and survival, including disease, cold stuns, harmful algal blooms, and predator attacks (Bolten et al., 2011). Often, cold-stunned turtles with external injuries die from factors related to decreased metabolic function that results from exposure to low temperatures, not from the injury itself (Innis et al., 2009). Predator-prey relationships are difficult to observe, especially in the ocean, and there is limited information available on the impacts that predation may have on sea turtle populations (Heithaus et al., 2002). Tiger sharks (*Galeocerdo cuvier*) and white sharks (*Carcharodon carcharias*) are the main predators of adult sea turtles and may influence population sizes (Witzell, 1987; Fergusson et al., 2000). Loggerheads are more likely to have shark bite injuries compared to green turtles, likely because they are slower and less maneuverable (Heithaus et al., 2002). In Florida, USA, ~4.3% of loggerhead strandings are due to shark bite injuries (Foley et al., 2017). Compared to predator attacks, anthropogenic injuries are more prevalent in sea turtles (Archibald & James, 2018). The energetic costs of such injuries on sea turtles are not well understood and further investigation is warranted (Heithaus et al., 2005).

Loggerhead and green sea turtles are the two most common sea turtle species found in Florida, USA (FFWCC, 2018), with both of these organisms considered threatened under the United States Endangered Species Act (Conant et al., 2009; Seminoff et al., 2015). Many anthropogenic threats place these organisms at risk for population declines; therefore, it is important to identify and quantify all threats to gather an accurate picture of what is primarily impacting local populations. Analyses of stranding data have been influential in understanding what threats are contributing most to sea turtle stranding and mortality, but data on mortality of sea turtles impacted by boats are limited (Kopsida et al., 2002; Hazel & Gyuriz, 2006; Singel et al., 2007; Casale et al., 2010; Bolten et al., 2011; Denkinger et al., 2013). Stranding data provides information on how many sea turtles die due to boat collisions and entanglements and how many are dispatched to rehabilitation facilities. However, part of the story is missing: how many turtles are injured and never strand? Better understanding the threats to sea turtles, by evaluating live turtles and mortality in rehabilitation facilities, is important for their conservation.

OBJECTIVES

The objectives of this study were to:

(1) determine prevalence and cause (anthropogenic versus natural) of external injuries (fresh and healed) on nesting loggerhead sea turtles in Juno and Jupiter Beaches, Florida, USA;

(2) compare natural injuries (predator attacks) to anthropogenic injuries on nesting loggerhead turtles; and,

(3) conduct a multi-year retrospective analysis of boat-related injury rehabilitation data from Florida Fish and Wildlife Conservation Commission (FWC) in order to calculate probability of mortality for loggerhead and green sea turtles injured by boats.

PREDICTIONS

(1) Nesting loggerhead turtles on Juno and Jupiter Beaches, Florida, USA, will have a higher prevalence of anthropogenic injuries compared to non-anthropogenic injuries.

(2) Larger boat-related injuries, according to percent area, length and width, will be associated with higher mortality rates than smaller boat injuries in sea turtles admitted to rehabilitation facilities in Florida, USA.

(3) Sea turtles with injuries limited to flipper and lateral carapace damage will have lower rehabilitation mortality rates than turtles with injuries on the head or the medial carapace (i.e., on the vertebral scutes).

(4) Sea turtles stranding in cooler months will have a higher mortality rate compared to turtles stranding in warmer months in sea turtles admitted to rehabilitation facilities in Florida, USA.

METHODOLOGY

STUDY SITE: NESTING BEACH

Palm Beach County hosts the highest number of loggerhead nests annually in Florida, USA, with 28,790 nests laid in 2019 alone (FFWCC, 2020). With such high numbers of nesting loggerheads, it provides a good location for data collection. The study sites, Juno and Jupiter Beaches (12.26 km), are located in Palm Beach County near Loggerhead Marinelife Center. Juno and Jupiter Beaches have been monitored for sea turtle nesting activity annually since the 1980s and host 40–50% of the county's total loggerhead nesting activity. Therefore, this important nesting population was predicted to serve as a good representation of the southeastern Florida loggerhead recovery unit as a whole, which in turn is the largest in the Atlantic Ocean (Shamblin et al., 2011).

DATA COLLECTION

The field portion of this project took place during peak loggerhead nesting season from 17 June–13 July, 2019. The nesting beaches were patrolled nightly from 21:00–03:00 using all-terrain vehicles. Approximately 4,000–10,000 loggerhead nests are laid each year on Juno and Jupiter Beaches (LMC, unpublished data); this equates to ~800–2500 individual females (using an estimated clutch frequency of 4–6 nests/season; Tucker, 2010). Turtles were approached either: (1) during their nesting fixed action pattern during which they are generally unresponsive to stimuli; or (2) during the camouflaging stage (i.e., post oviposition). No turtles were handled, tagged, or photographed before eggs were laid. A complete external exam was conducted to visually assess each turtle for the presence of external injuries.

The following information was recorded from each loggerhead turtle encountered (Table 1): minimum and maximum straight carapace length (SCL_{min} and SCL_{max}), straight carapace width (SCW), minimum and maximum curved carapace length (CCL_{min} and CCL_{max}), and curved carapace width (CCW), after Wyneken (2001). If an injury was present, the following information was also recorded: type of injury (if known; e.g., entanglement, hook, boat strike, predator attack), location of the injury (e.g., head, extremity, lateral carapace, medial carapace), and condition of the injury (e.g., fresh, partially healed, healed; Table 2). If the injury was a series of parallel strikes, blunt force trauma, or a "clean" cut, it was identified as a boat strike injury (Work et al., 2010). Injuries were categorized as entanglement if lacerations encircled the neck or appendage, or if gear (which was removed from the animal during oviposition) was still present on the turtle (Innis et al., 2010; Archibald & James, 2018). Hook injuries were identified by puncture wounds, by the presence of healing, raised scar tissue where the puncture occurred (Watson et al., 2005), or when a small piece of the maxilla was removed. Predator attacks were identified if the injury was crescent shaped and/or included parallel rake marks (Heithaus et al., 2002). Scarring tissue, with pink/yellow skin, was used to describe an injury that was still in the process of healing and had not yet become a completely healed scar (Table 2).

Table 1. Data collected from each nesting female and rehabilitation patient.

Turtle ID	Morphometrics	Injury condition	Injury type	Injury location	Injury Severity	Injury size
Flipper tags	SCL_{min}	Healed	Entanglement	Head	No injury	% area
PIT tags	SCL_{max}	Partially healed	Hook	Extremity	Minor injury	Total length
	CCL_{min}	Fresh	Boat strike	Medial carapace	Intermediate injury	Average length
	CCL_{max}		Predator attack	Lateral carapace	Severe injury	Minimum length
	SCW		Unknown	Plastron		Maximum length
	CCW					Total width
						Average width
						Minimum width
						Maximum width
						Number of injuries

Table 2. Injury condition definitions for loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) turtles from Florida, USA.

Injury condition	Definition
Fresh	Open wound; no scarring tissue present; blood present
Partially healed	Wound beginning to close; scarring tissue present; pink/yellow skin
Healed	Closed wound, no scarring tissue present; scar may still be present

Untagged turtles were tagged with Inconel flipper (National Band and Tag Company, Newport Kentucky, USA) and MiniHPT8 pre-loaded sterile syringe passive integrated transponder (PIT) tags (Biomark®, Boise, Idaho, USA). All handling and tagging of sea turtles were conducted by personnel authorized on the relevant FWC Marine Turtle Permit (MTP #205), and followed FWC guidelines highlighted in their Marine Turtle Conservation Handbook (FFWCC, 2016). Photographs, using red external light emitting diode headlamps, were taken of the turtles and their injuries. Images provided a way to document and confirm cause of injury. The entire carapace and head were included in each image. Photos were taken of the dorsal surface of the turtle at a 90° angle. If the injury was from an entanglement or hook, photographs from different perspectives (e.g., lateral, anterior) were taken in order to better categorize the injury; these injuries were not measured. Injury types that could not be easily classified were confirmed by two experienced veterinarians. The computer software program ImageJ was used to further analyze the area of the boat injuries using the images taken during field work (Rasband, 2016).

FWC DATA

Data from FWC were used to conduct a retrospective analysis of sea turtle rehabilitation patients in order to determine probability of mortality of sea turtles entering Florida, USA, rehabilitation facilities that were impacted by boats. Stranding data from 2008–2019 were used for the analysis and included 763 cases, of which 318 were analyzed in ImageJ (FFWCC, 2018). Images were not utilized if they were not taken dorsally and/or at a 90° angle. Other types of injuries (e.g., entanglement, hook, predator attack, fibropapillomatosis tumors) that were present in conjunction with boat strike injuries, were noted. Intake data of sea turtles admitted to Florida's sea turtle rehabilitation facilities included: SCL_{min}, SCL_{max}, SCW, CCL_{min}, CCL_{max}, CCW, flipper and PIT tags if present, stranding location, stranding date, wounds/abnormalities present, and final case outcome (e.g., healthy release, euthanized, died). Sea turtles that were dead on arrival, died in transport, or died in rehabilitation without euthanasia were categorized as "died" for their case outcome. To evaluate mortality, turtles that were euthanized or died at the rehabilitation facility were categorized as "1", while turtles that were released were categorized as "0" for statistical analysis. Case outcome (e.g., healthy release, euthanized, died) and mortality (e.g., lived, died) were analyzed independently, since euthanasia can be variable and is determined by the veterinarian at the rehabilitation facility. Photographs of every stranded sea turtle with a boat strike were used to identify the precise location of where the injuries were located (e.g., head, extremities, lateral carapace, medial carapace, plastron) and to estimate wound size.

IMAGEJ 1.47v SOFTWARE

The SCL_{min} was typically used to scale the images from pixels to centimeters; however, SCW was used for scale if the posterior or anterior end of the carapace was missing or the SCL_{min} was not available. If the posterior or anterior end of the carapace was missing, and percent area calculations were not possible, injury length and/or width measurements were recorded so that these turtles could be included in the length and width analyses. The polygon drawing tool in ImageJ was used to trace the entire carapace and measure total carapace area in addition to tracing the boat injuries to measure the total area of the injuries. The straight-line tool was used to measure length and width of the injuries. The area of the boat strike injury was divided by the area of the carapace to determine carapace injury percent (Table 3). The ratio of injury length to SCL_{min} and injury width to SCW was calculated in order to analyze injury size between turtles of different lengths.

The polygon drawing tool in ImageJ was used to measure the areas of the turtles' head, carapace, and injury(ies). To measure head area, the outside of the head was traced to the last temporal scale, followed by the addition of a straight line that was drawn across the neck to the temporal scale on the other side of the head (the eyes were included in head area). If a barnacle was present on the edge of the carapace or a minor amount of carapace was missing due to the boat strike injury, a straight line was drawn through the obtrusion or missing carapace piece. When multiple injuries were present, the sum, average, minimum, and maximum of all the lengths and widths were used for analysis. Figures 2 and 3 show examples of how measurements were made in ImageJ. The total number of injuries was also recorded. All images were used to determine the severity of injury defined in Table 4 (Rasband, 1997–2016).

Table 3. Definition of variables for stranded loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) sea turtles from Florida, USA.

Abbreviation	**Variable**	**Definition**
A_c	Carapace area (cm^2)	Total dorsal area of the carapace
A_i	Injury area (cm^2)	Total area of all injuries on the carapace
A_{st}	Standardized injury area	$A_i / A_c \times 100$
L_{total}	Total injury length	Sum of all the injury lengths if multiple present
$L_{average}$	Average injury length	Mean of all the injury lengths if multiple present
L_{max}	Injury length maximum	Largest injury length if multiple present
L_{min}	Injury length minimum	Smallest injury length if multiple present
W_{total}	Total injury width	Sum of all the injury widths if multiple present
$W_{average}$	Average injury width	Mean of all the injury widths if multiple present
W_{max}	Injury width maximum	Largest injury width if multiple present
W_{min}	Injury width minimum	Smallest injury width if multiple present
Number of injuries	Injury count	Total number of injuries present on the turtle
Injury condition	Healing stage of the injury	Healed, partially healed, fresh
Injury type	How the injury occurred	Entanglement, hook, boat strike, predator attack
Injury location	Anatomic location of each described injury	Head, extremity, medial carapace, lateral carapace
Number of locations	Number of anatomic locations	Number of anatomic locations impacted by the boat strike injury

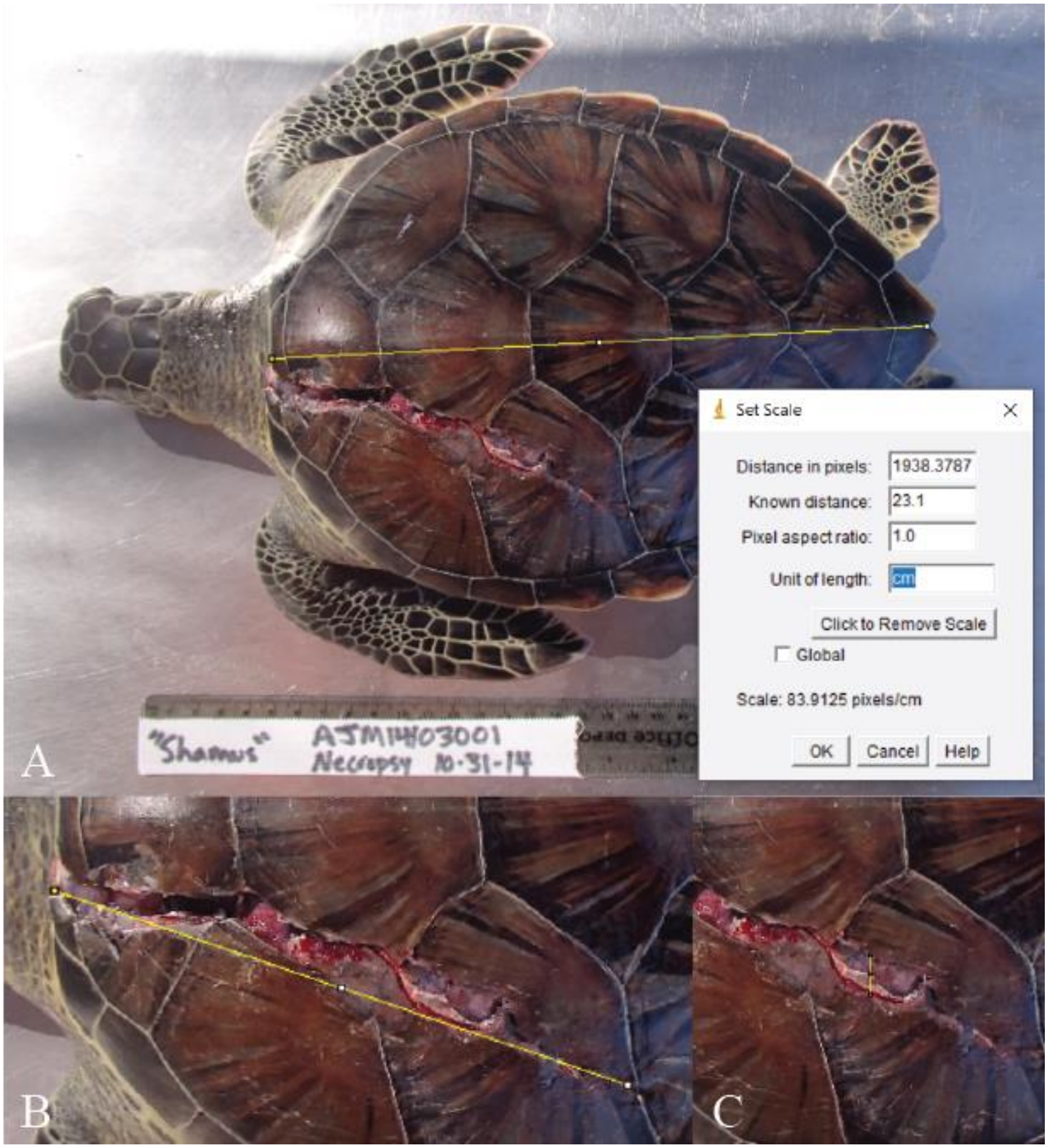

Figure 2. Using the straight-line tool in ImageJ. (A) Example of using minimum straight carapace length (SCL_{min}) in a juvenile green turtle (*Chelonia mydas*) to set the scale in images received from Florida Fish and Wildlife Conservation Commission (FWC). The known distance in the pop-up sets the distance in pixels from the image to the actual size of the turtle in centimeters. (B) Example of using the straight-line tool to measure the maximum length of the injury. (C) Example of using the straight-line tool to measure the maximum width of the injury.

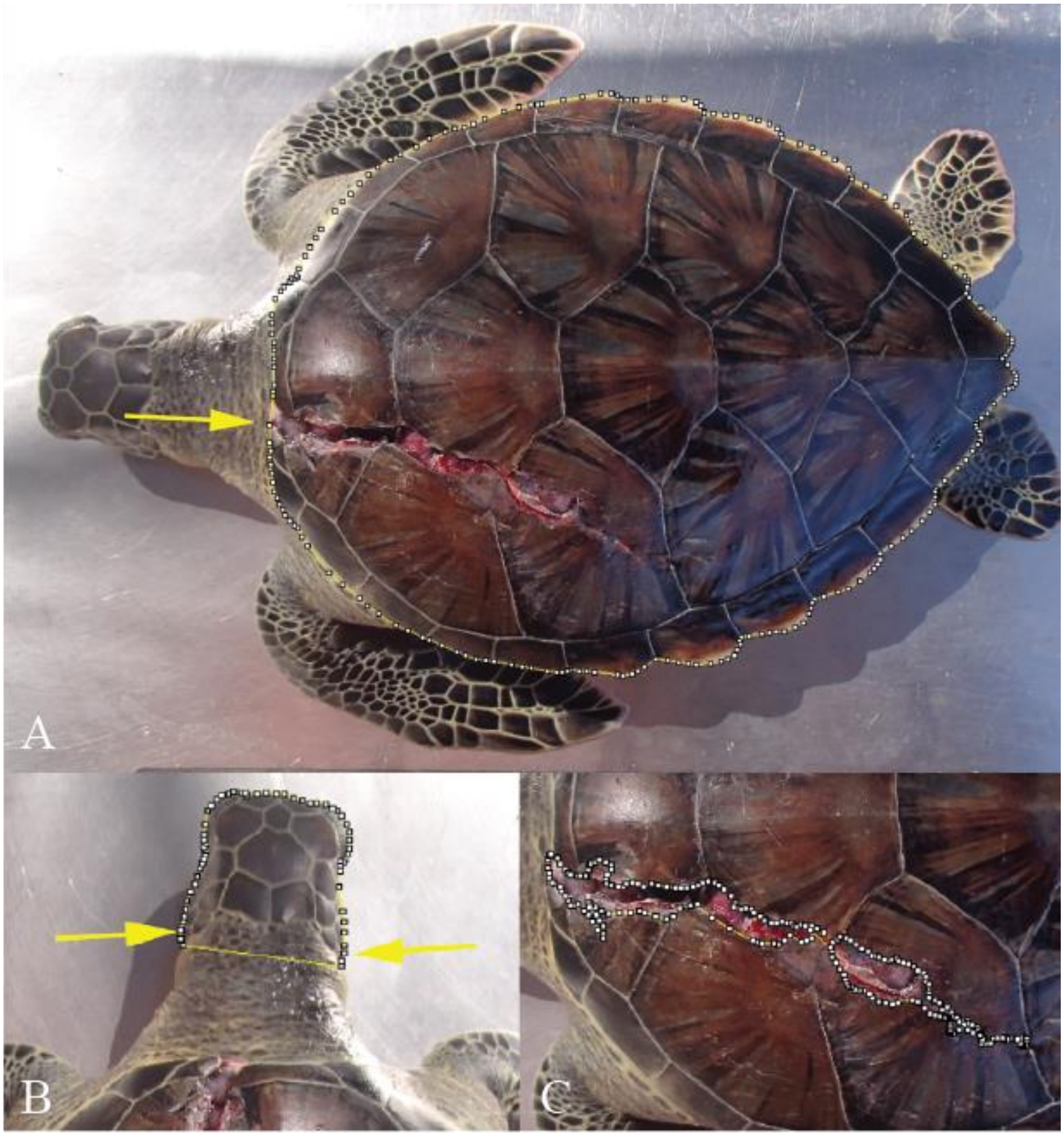

Figure 3. Using the polygon tool in ImageJ. (A) Example of using the polygon tool to trace the edge of the entire carapace of a juvenile green turtle (*Chelonia mydas*). Note that where the injury reaches the edge of the anterior carapace (arrow), a straight line was drawn to the other side of the intact carapace. (B) Example of using the polygon tool to trace the turtle's head. Once reaching the temporal scales (arrows) on each side of the head a straight line was drawn through the neck. (C) Example of using the polygon tool to trace the entire area of the injury.

Table 4. Injury severity categories for stranded loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) sea turtles from Florida, USA.

Category	Score	Definition
Minor injury	1	The injury covered approximately <5% of the carapace and did not enter the body cavity. If a head injury was present it was superficial.
Intermediate injury	2	The injury covered approximately <9% of the carapace and may enter the body cavity. A head injury was considered intermediate if the injury did not slice through the skull.
Severe injury	3	The injury covered approximately >5% of the carapace and entered the body cavity or if a head injury was present it sliced through the skull. The injuries were not healed.

STATISTICAL ANALYSES

To determine if there existed a higher prevalence of anthropogenic injuries (e.g., entanglement, hook, and boat strike) compared to non-anthropogenic injuries (e.g., predator attack) present on nesting loggerhead sea turtles, Fisher's exact tests with Bonferroni adjusted post-hoc tests were conducted. Fisher's exact tests were used when groups in the contingency table had a sample size less than or equal to five ($N \leq 5$).

For the FWC/stranding data, life-stage class (Table 5) was assigned according to SCL_{min} measurements, while injury sizes were categorized into thirds. Injury percent area, average injury length to SCL_{min} ratio, and average injury width to SCW ratio values that fell within the first 33.3% of the data were designated as "small" injuries, while injuries that fell between 33.4–66.7% of the data were designated as "medium" injuries, and injuries that fell between 66.8–100% of the data were designated as "large" injuries (Table 6). To test for significant differences between stranded loggerhead or green case outcomes (e.g., died, euthanized, released) in relation to SCL_{min}/life-stage class, carapace injury area category, injury length category, injury width category (Table 6), injury condition (e.g., fresh, partially healed, healed), injury severity (e.g., minor (1), intermediate (2), severe(3)), and number of anatomic locations (e.g., head, lateral or medial carapace, extremities, plastron) with injuries (e.g., 1, 2, ≥3), 3x3 contingency analyses were run. To determine if there was a significant difference in case outcome according to the number of injuries (e.g., 1, 2, 3, ≥4), a 3x4 contingency analysis was run. Stranding months were categorized into "cold" and "hot" seasons, with December through April falling into the "cold" season category and May through November falling into the "hot" season category. Season categorization was based on data provided by He et al. (2003), that found sea surface temperature (SST) to be lower (15–24.5°C) on average in December, January, February, March, and April when compared to the rest of the year (>24.5°C) in Florida, USA. To test for significant differences between case outcome with regards to injury anatomic location presence (e.g., head injury present/absent, lateral carapace injury present/absent, etc.) and stranding season (e.g., hot, cold), 3x2 contingency analyses were run.

Table 5. Loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) turtle life-stage class designations according to SCL_{min} (Bjorndal et al., 2000; Bresette et al., 2010; FFWCC, 2016).

Loggerhead Life-Stage Class	**Green Life-Stage Class**
Juvenile (<58cm)	Juvenile (<65cm)
Subadult (58–80cm)	Subadult (65–83cm)
Adult (>80cm)	Adult (>83cm)

Table 6. Injury size categories for stranded loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) turtles from Florida, USA.

Category	**Carapace Injury Area Percent Range (*N*)**	**Average Injury Length to SCL_{min} Ratio Range (*N*)**	**Average Injury Width to SCW Ratio Range (*N*)**
Small	0.01–1.04% (*N* = 95)	0.004–0.093 (*N* = 92)	0.008–0.126 (*N* = 94)
Medium	1.05–2.46% (*N* = 96)	0.094–0.239 (*N* = 92)	0.127–0.250 (*N* = 95)
Large[1]	2.47–11.14% (*N* = 95)	0.240–0.865 (*N* = 92)	0.25–0.871 (*N* = 94)

[1]Boxplots were used to test for outliers. Every "large" category had outliers; these values were not excluded from statistical analyses. Carapace injury area had 17 outliers; these values were ≥ 6.87%. Average injury length to SCL_{min} ratio had 9 outliers; these values were ≥ 0.60. Average injury width to SCW ratio had 7 outliers; these values were ≥ 0.62.

Additionally, to test the association between the independent variables (SCL_{min}, carapace injury percent, average injury length to SCL_{min} ratio, average injury width to SCW ratio, number of injuries and number of injury locations) and mortality (died, survived), a multiple logistic regression with a binomial distribution and logit link was run for each species. Average injury length to SCL_{min} ratio, total injury length to SCL_{min} ratio, minimum injury length to SCL_{min} ratio, and maximum injury length to SCL_{min} ratio were strongly correlated (VIF > 8). Average injury width to SCW ratio, total injury width to SCW ratio, minimum injury width to SCW ratio, and maximum injury width to SCW ratio were also highly correlated (VIF > 8). Thus, four independent regression models for mortality were compared (Appendices A & B). The model using average injury length to SCL_{min} ratio, and average injury width to SCW ratio, had a comparably low Akaike information criterion (AIC) value for loggerheads, with low (≤2.2) variance inflation factor (vif) values (Appendix A). The model using average injury length to SCL_{min} ratio, and average injury width to SCW ratio, had the lowest AIC value for green turtles (Appendix B). Therefore, average injury length to SCL_{min} ratios and average injury width to SCW ratios are used throughout the results, in order to keep variables between species consistent and comparable. To evaluate the overall fit of the model *zoo* version 1.8.8

(Zeileis et al., 2005) and *aod* version 1.3.1 (Lesnoff & Lancelot, 2019) were used to run likelihood ratio tests and Wald's tests, respectively.

To test for significant differences between loggerhead or green turtle mortality (e.g., died, survived) in relation to injury condition and severity, 2x3 contingency analyses were run. To test for significant differences between loggerhead or green turtle mortality in relation to injury anatomic location presence and stranding season 2x2 contingency analyses were run.

The *ggplot2* version 3.3.0 was used to produce figures (Wickham 2016). Statistical significance was set to $P \leq 0.05$. All statistical tests were performed using R 3.5.3 (R Core Team, 2019).

RESULTS

INJURY PREVALENCE IN NESTING FEMALES

Three hundred nesting loggerhead sea turtles were assessed during the 2019 season for this study, accounting for ~14–21% of the population (8,724 loggerhead nests were laid on Juno and Jupiter Beaches in 2019, equating to ~1,400–2,200 females based on a clutch frequency of 4–6 nests/season; Tucker 2010). Average SCL_{min} and SCL_{max} for nesting loggerheads were 88.1 ± 6.4 cm and 89.0 ± 6.4 cm, respectively. Of the turtles assessed, 23.7% (N = 71) showed signs of some type of external injury. These injuries were further identified between five different groups: entanglement (N = 2), hook (N = 4), boat (N = 30), shark (N = 8), and unknown (N = 31). The unknown injuries were excluded from the statistical analysis when determining if there were significant differences based on injury type. There were significantly more boat strike injuries compared to entanglement, hook, or shark injuries (Fisher's exact test: $P < 0.001$; Fig. 4). Four turtles had more than one type of injury present. Each of these was counted as a separate injury in the analysis. The turtles with multiple injury types had the following combinations: hook and boat, entanglement and boat, boat and unknown, and hook and unknown. Unknown injuries primarily consisted of damage to the extremities (53.6%) and/or the lateral carapace, which were usually smaller injuries and therefore more difficult to classify (Fig. 5).

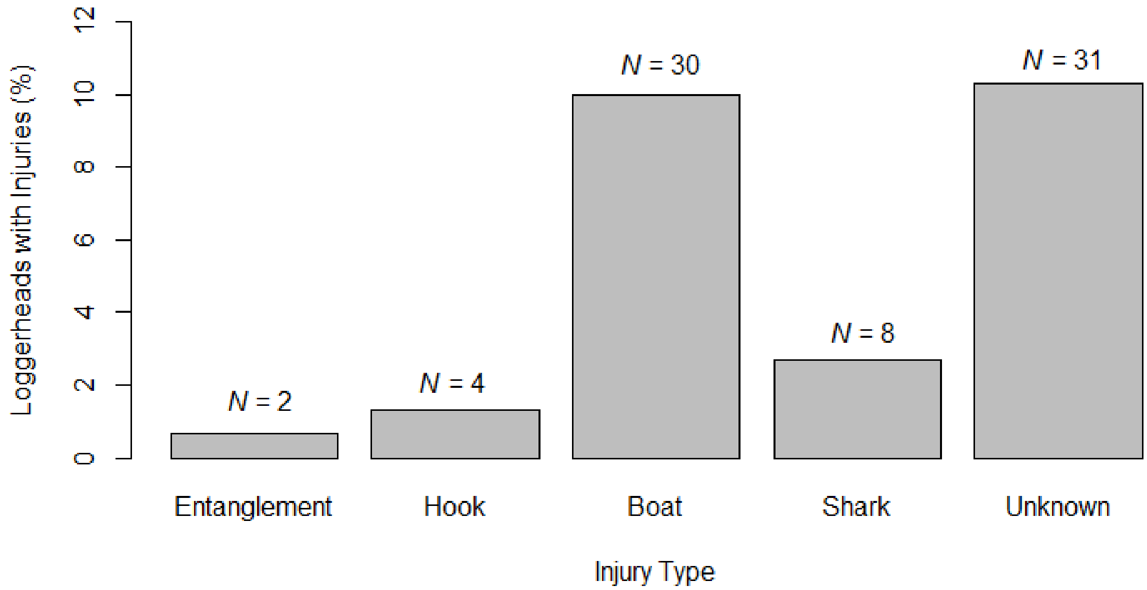

Figure 4. Injury prevalence data for nesting loggerhead sea turtles (*Caretta caretta*) from Juno and Jupiter Beaches, Florida, USA. Approximately 24% (*N* = 71) of nesting loggerheads had injuries, with the largest source of injuries from known causes coming from interactions with boats at 10.0%, followed by shark injuries at 2.7%. The number of turtles with each injury type is represented by the number above each column.

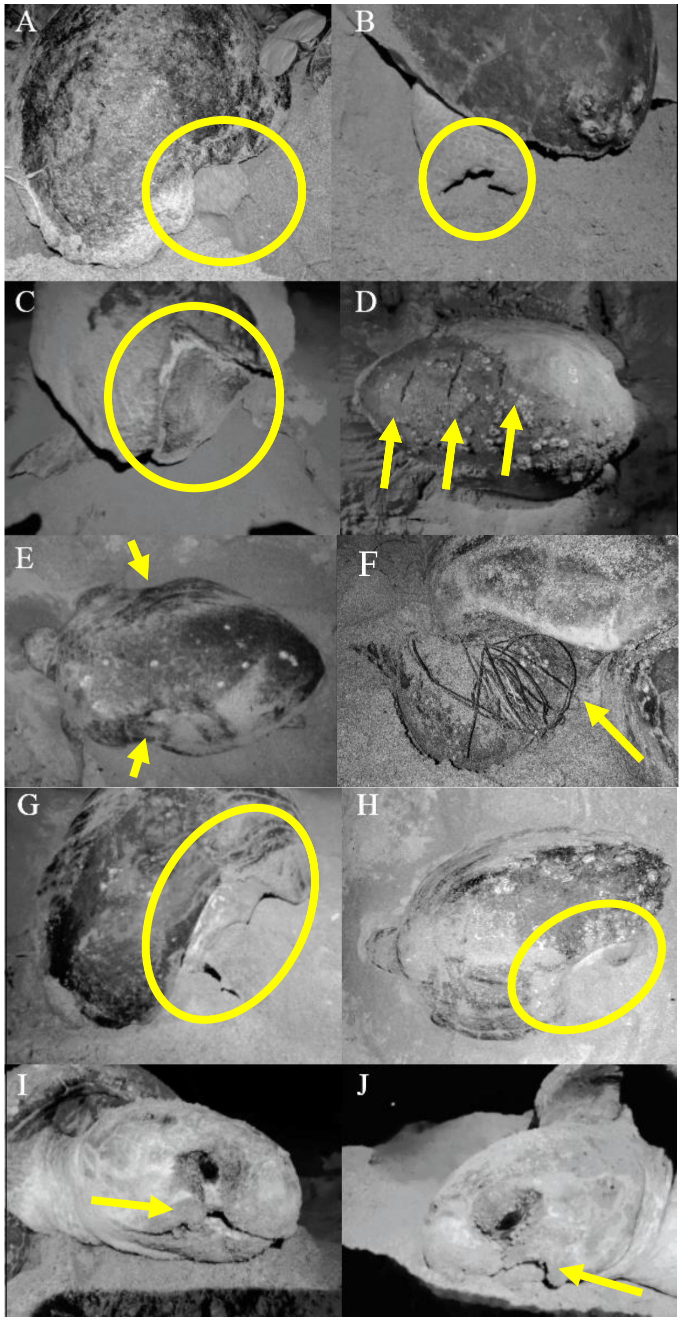

Figure 5. Examples of external injuries that were identified on nesting loggerhead sea turtles (*Caretta caretta*) from Juno and Jupiter Beaches, Florida, USA. (A) small, unknown injury to the right lateral carapace; (B) unknown injury to the left rear flipper; (C, D) boat strike injuries; (E) concave injuries on the lateral carapace, likely due to an entanglement that occurred earlier in the turtle's life that constricted the carapace during growth; (F) fishing line entangled around the right front flipper; (G, H) crescent-shaped amputation of the lateral carapace, likely from a shark interaction; (I, J) pieces of maxilla missing, identified as hook injuries.

Most (94.4%) of the injuries encountered on the nesting females were healed, with only four turtles (5.6%) having partially healed injuries, where pink and yellow tissue was present around a closing wound. Approximately 5.6% (N = 4) of injuries included the head (Table 7), which were all categorized as hook wounds. Lateral injuries that were located only on the extremities, lateral carapace, or both, constituted 59.1% of all injuries (Table 7). On average, carapace injury area percent of nesting turtles was 1.56 ± 1.52% (range: 0.20–6.58%). The average injury length to SCL_{min} ratio was 0.19 ± 0.13 (range: 0.02–0.52). The average injury width to SCW ratio was 0.18 ± 0.14 (range: 0.02–0.52).

Table 7. Count and percentage data based on injury location for the 71/300 (23.7%) nesting loggerhead sea turtles (*Caretta caretta*) from Juno and Jupiter Beaches, Florida, USA, with external injuries.

Injury Location	**Count**	**Percentage**
Extremity	15	21.1%
Head	1	1.4%
Head & Extremity	2	2.8%
Head & Medial & Lateral Carapace	1	1.4%
Medial & Lateral Carapace	19	26.8%
Medial & Lateral Carapace & Extremity	5	7.0%
Lateral Carapace	24	33.8%
Lateral Carapace & Extremity	3	4.2%
Medial Carapace & Extremity	1	1.4%

STRANDING/REHABILITATION ANALYSIS

CASE OUTCOME

<u>Loggerheads</u>

Injuries on 64 loggerhead turtles that entered rehabilitation facilities in Florida, USA, during 2009–2019 were analyzed for this study. The average SCL_{min} and SCL_{max} for the turtles analyzed were 71.8 ± 11.7 cm (range: 48.8–103.2 cm) and 73.3 ± 11.6 cm (range: 49.1–104.1 cm), respectively.

There were no significant differences in SCL_{min}/life-stage class, carapace injury area percent, average injury length to SCL_{min} ratio, average injury width to SCW ratio, injury severity, number of injuries, number of injured anatomic locations, presence of head, lateral carapace, medial carapace, extremity, or plastron injuries, or stranding season for rehabilitating loggerheads based on case outcome (Fisher's exact test: $P > 0.05$). There were significant differences in case outcomes based on injury condition (Fisher's exact test: $P < 0.001$; Fig. 6D), as significantly fewer turtles with fresh injuries were released ($N = 2$) versus died ($N = 9$) or were euthanized ($N = 15$; Fisher's exact test: $P < 0.001$).

<u>Green turtles</u>

Injuries on 254 green turtles that entered rehabilitation facilities in Florida, USA, during 2009–2019 were analyzed for this study. The average SCL_{min} and SCL_{max} for the green turtles analyzed were 40.8 ± 16.7 cm (range: 18.7–104.0 cm) and 41.3 ± 16.7 cm (18.8–104.0 cm), respectively.

Significant differences were observed in carapace injury area percent (Pearson: $\chi^2 = 11.16$; d.f. = 4; $P = 0.025$; Fig. 7A), average injury width to SCW ratio (Pearson: $\chi^2 = 20.23$; d.f. = 4; $P < 0.001$; Fig. 7B), and lateral carapace injury presence (Pearson: $\chi^2 = 6.03$; d.f. = 2; $P = 0.049$; Fig. 7C) for green turtles with regard to case outcome. No significant differences were observed in case outcome according to SCL_{min}/life-stage class, average injury length to SCL_{min} ratio, number of injuries, number of injured anatomic locations, presence of head, medial carapace, extremity, or plastron injuries, or stranding season (Pearson χ^2: $P > 0.05$).

Green turtles with medium injuries (by area) were significantly more likely to die ($N = 36$) than survive to be released ($N = 18$; Fisher's exact test: $P = 0.013$; Fig. 7A). There were also significantly more green turtles with large injuries that were euthanized ($N = 30$) than were released ($N = 13$; Fisher's exact test: $P = 0.009$; Fig. 7A). Green turtles with small injury widths were significantly more likely to die unassisted ($N = 32$; Fisher's exact test: $P = 0.004$) or survive to be released ($N = 31$; Fisher's exact test: $P = 0.007$) than they were to be euthanized ($N = 13$). Conversely, green turtles with large injury widths were significantly more likely to be euthanized ($N = 38$; Fisher's exact test: $P < 0.001$; Fig. 7B) than they were to be released ($N = 14$). There were significantly fewer green turtles with lateral carapace injuries that were released ($N = 51$), compared to green turtles with lateral carapace injuries that died ($N = 84$; Fisher's exact test: $P = 0.002$; Fig. 7C).

There were also significant differences in case outcomes of green turtles based on injury condition (Pearson: $\chi^2 = 37.67$; d.f. = 4; $P < 0.001$; Fig. 7D), as there were more individuals with healed injuries that were released ($N = 23$) than those that died ($N = 7$) or were euthanized ($N = 7$; Fisher's exact test: $P < 0.001$). There were no significant differences in case outcomes for green turtles with injury severity level 1, while significantly fewer turtles with injury severity level 2 were released ($N = 21$) compared to those that died ($N = 47$) or were euthanized ($N = 41$). Significantly more green turtles with injury severity level 3 were euthanized ($N = 15$) than those that died ($N = 6$; Fisher's exact test: $P < 0.001$; Fig. 7E). No turtles categorized as injury severity level 3 survived to be released.

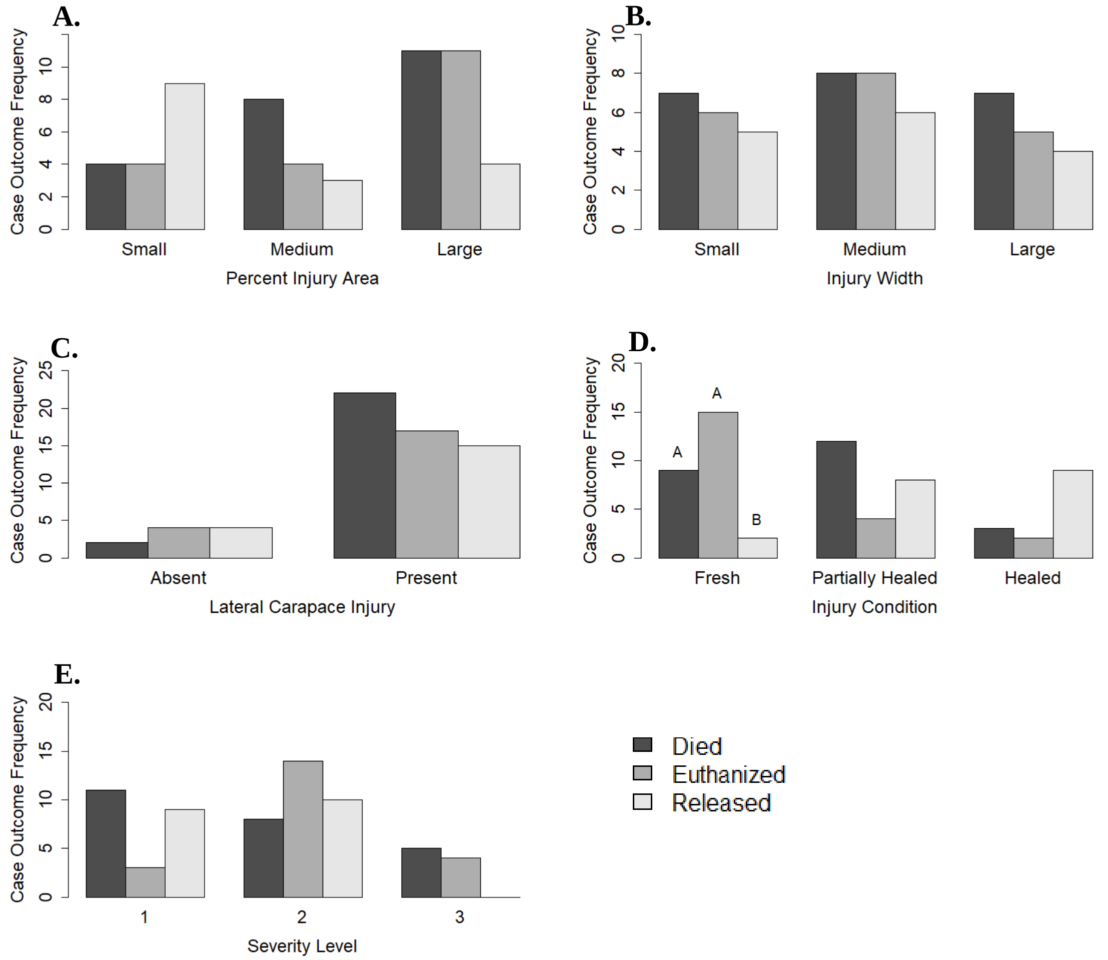

Figure 6. Case outcome frequency of stranded loggerheads (*Caretta caretta*) from Florida, USA, based on (A) injury area, (B) injury width, (C) lateral carapace injury presence, (D) injury condition, and (E) severity level. Legend in the bottom right-hand corner displays case outcome. Letters above the bar plots represent significance differences found from Bonferroni corrected post hoc tests.

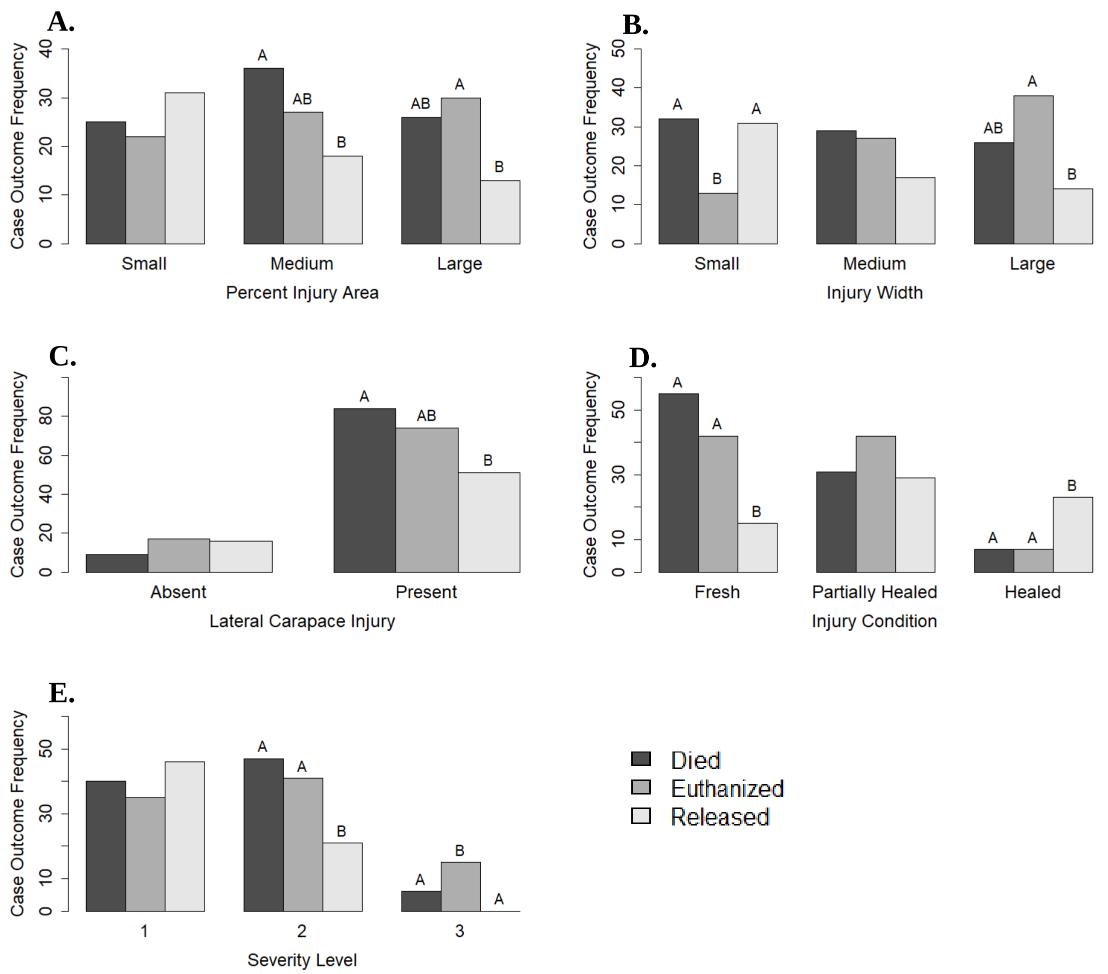

Figure 7. Case outcome frequency of stranded green turtles (*Chelonia mydas*) from Florida, USA, based on (A) injury area, (B) injury width, (C) lateral carapace injury presence, (D) injury condition, and (E) severity level. Legend in the bottom right-hand corner displays case outcome. Letters above the bar plots represent significance differences found from Bonferroni corrected post hoc tests.

PROBABILITY OF MORTALITY

Loggerheads

The multiple logistic regression model evaluating the relationships between SCL_{min}, carapace injury percent, average injury length to SCL_{min} ratio, average injury width to SCW ratio, number of injuries, and number of injured anatomic locations in loggerheads was significant (pseudo $R^2 = 0.24$; $P = 0.036$). The number of anatomic locations with an injury was a significant predictor of mortality (Table 8). The probability of loggerhead mortality increased with the number of impacted anatomic locations ($P = 0.041$; Fig. 8). Also, as the number of injured anatomic locations increased, more head or medial carapace injuries were present (Table 9). The probability of mortality was greater than 95% for turtles with four or more injured anatomic locations. For each additional injured anatomic location, the odds of a turtle dying in rehab (vs. surviving to be released) increased by a factor of 5.99 (e^{β}). In other words, a turtle with an injury in two anatomic locations is approximately 6 times more likely to die in rehab than a turtle with an injury in one anatomic location. The logistic model for loggerheads is a better fit than the intercept-only model (null model with no predictors), which is supported by the likelihood ratio test ($P = 0.036$), but not by the Wald test ($P = 0.250$).

Table 8. Coefficients of the multiple logistic regression model for stranded loggerhead (*Caretta caretta*) sea turtles in Florida, USA. Asterisk represents statistical significance ($P \leq 0.05$).

Predictor	**β**	**SE β**	**Z value**	**d.f.**	***P***	**e^{β} (odds ratio)**
Intercept	–1.98	3.99	–0.50	51	0.620	NA
SCL_{min}	–0.03	0.04	–0.76	51	0.447	0.97
Carapace Injury Area Percent	–0.06	0.18	–0.31	51	0.758	0.94
Average Injury Length to SCL_{min} Ratio	3.90	3.25	1.20	51	0.231	49.40
Average Injury Width to SCW Ratio	–1.32	3.08	–0.43	51	0.667	0.27
Number of Injuries	0.69	0.45	1.54	51	0.124	1.99
Number of Anatomic Locations	1.79	0.88	2.05	51	*0.041	5.99
Test			**χ^2**	**d.f.**	***P***	
Overall model evaluation						
Likelihood ratio test			13.46	5	*0.036	
Wald test			7.80	6	0.250	

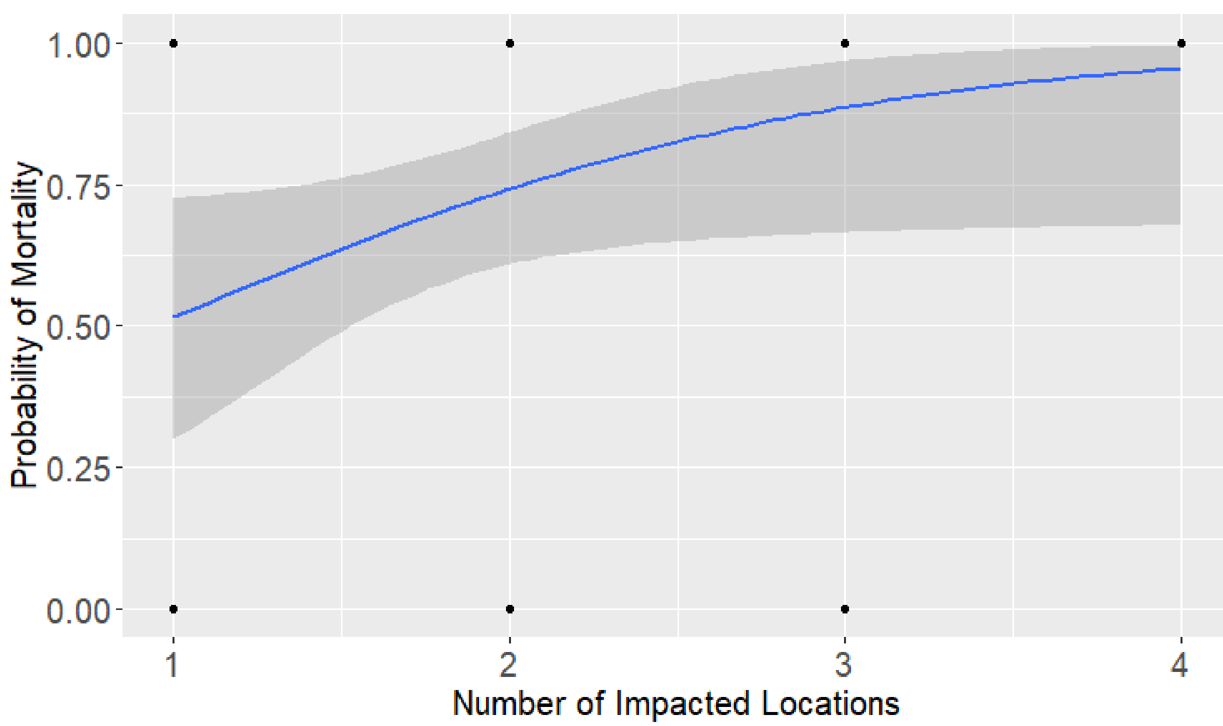

Figure 8. The relationship between the number of injury anatomic locations to mortality in stranded loggerheads (*Caretta caretta*) from Florida, USA. The shaded gray around the blue line represents standard error.

Table 9. Number of injured anatomic locations (%) for stranded loggerheads (*Caretta caretta*) from Florida, USA. Each column represents the percentage of turtles that had an injury in that location. In parentheses are the number of turtles over the total number of turtles with a given number of impacted anatomic locations.

Number of Impacted Anatomic Locations	Head	Medial Carapace	Lateral Carapace	Extremity	Plastron
1	31.3% (5/16)	31.3% (5/16)	37.5% (6/16)	0% (0/16)	0% (0/16)
2	2.4% (1/41)	95.1% (39/41)	100% (41/41)	0% (0/41)	2.4% (1/41)
3	40% (2/5)	100% (5/5)	100% (5/5)	60% (3/5)	0% (0/5)
4	50% (1/2)	100% (2/2)	100% (2/2)	100% (2/2)	50% (1/2)

Injury condition (e.g., healed, partially healed, fresh) was significantly related to mortality in loggerhead turtles (Fisher's exact test: $P < 0.001$). Loggerheads entering rehabilitation facilities with fresh injuries (Fisher's exact test: $P < 0.001$) and partially healed injuries (Fisher's exact test: $P = 0.04$) had a significantly higher probability of mortality compared to turtles with healed injuries. As injury condition improved, the probability of mortality decreased (Fig. 9A). There were no significant differences in mortality based on injury severity (Fisher's exact test: $P > 0.05$), presence of head (Fisher's exact test: $P > 0.05$), lateral carapace (Fisher's exact test: $P > 0.05$), medial carapace (Pearson χ^2: $P > 0.05$), extremity (Fisher's exact test: $P > 0.05$), or plastron injuries (Fisher's exact test: $P > 0.05$), or stranding season (Pearson χ^2: $P > 0.05$).

Green turtles

The multiple logistic regression model evaluating the relationships between SCL_{min}, carapace injury percent, average injury length to SCL_{min} ratio, average injury width to SCW ratio, number of injuries, and number of injured anatomic locations in green turtles was significant (pseudo $R^2 = 0.09$; $P < 0.001$). The average injury width to SCW ratio was a significant predictor of mortality (Table 10). The probability of green turtle mortality increased with average injury width to SCW ($P = 0.003$; Fig. 10). Once the average injury width to SCW ratio exceeded 0.54 there was more than a 90% chance of green turtle mortality. Therefore, the larger the injury, the more likely that a green turtle entering a rehabilitation facility would not survive. For each one-unit increase in average injury width to SCW ratio, the odds of a turtle dying in rehabilitation increased by a factor of 217.02 (e^{β}). The logistic model is a better fit than the intercept only model (null model with no predictors), which is supported by the likelihood ratio test ($P <$ 0.001) and the Wald test ($P = 0.007$).

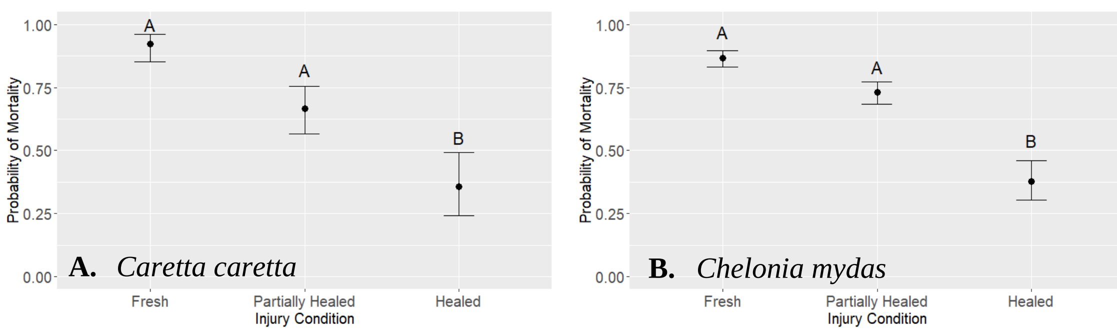

Figure 9. (A) Probability of mortality based on injury condition of stranded loggerhead turtles (*Caretta caretta*) from Florida, USA. (B) Probability of mortality based on injury condition of stranded green turtles (*Chelonia mydas*) from Florida, USA. The solid black dot represents the mean and the whiskers on either side of the mean represents the 95% confidence interval.

Table 10. Coefficients of the multiple logistic regression model for stranded green (*Chelonia mydas*) turtles in Florida, USA. Asterisk represents statistical significance ($P \leq 0.05$).

Predictor	**β**	**SE β**	**Z value**	**d.f.**	***P***	**e^{β} (odds ratio)**
Intercept	–0.28	0.79	–0.36	219	0.718	NA
SCL_{min}	–0.01	0.01	–1.46	219	0.145	0.99
Carapace Injury Area Percent	–0.15	0.12	–1.29	219	0.198	0.86
Average Injury Length to SCL_{min} Ratio	3.11	1.59	1.95	219	0.051	22.42
Average Injury Width to SCW Ratio	5.38	1.79	3.01	219	*0.003	217.02
Number of Injuries	0.04	0.19	0.22	219	0.829	1.04
Number of Anatomic Locations	0.33	0.30	1.09	219	0.276	1.39
Test			**χ^2**	**d.f.**	***P***	
Overall model evaluation						
Likelihood ratio test			2.34	6	*<0.001	
Wald test			17.70	6	*0.007	

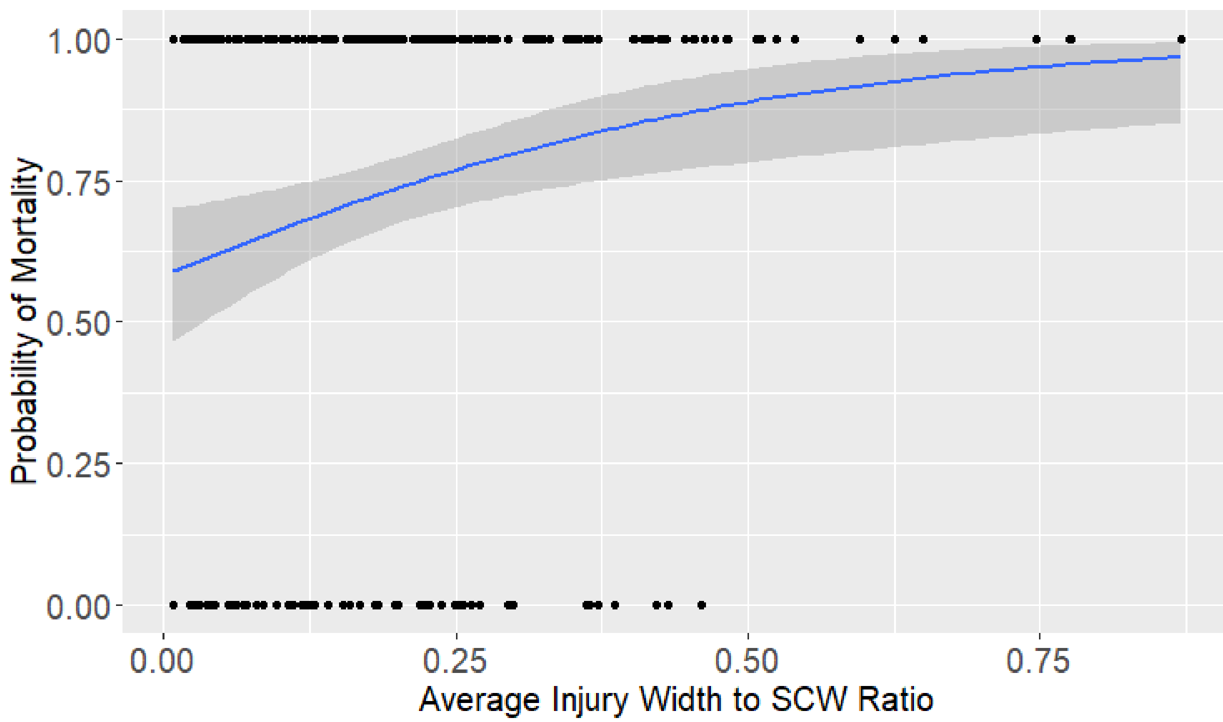

Figure 10. The relationship between average injury width to SCW ratio to mortality in stranded green turtles (*Chelonia mydas*) from Florida, USA. The shaded gray around the blue line represents standard error.

Injury condition (e.g., healed, partially healed, fresh) was also significantly related to mortality in green turtles (Pearson: $\chi^2 = 34.25$; d.f. = 2; $P < 0.001$). Green turtles entering rehabilitation facilities with fresh and partially healed injuries had a significantly higher probability of mortality compared to turtles with healed injuries (Fisher's exact test: $P < 0.001$). As injury condition improved, the probability of mortality decreased. Injury severity (e.g., minor, intermediate, severe) also had a significant effect on green turtle mortality (Fisher's exact test: $P < 0.001$). Green turtles with an injury severity level 2 had a significantly higher probability of mortality compared to those with severity level 1. The probability of mortality increased along with injury severity level (Fig. 11B). Severity level 3, perfectly predicts the outcome, all green turtles with an injury severity level of 3 died. There were no significant differences in mortality according to presence of head (Pearson χ^2: $P > 0.05$), lateral carapace (Pearson χ^2: $P > 0.05$), medial carapace (Pearson χ^2: $P > 0.05$), extremity (Fisher's exact test: $P > 0.05$), or plastron injuries (Fisher's exact test: $P > 0.05$; Table 11), or stranding season (Pearson χ^2: $P > 0.05$) for green turtles.

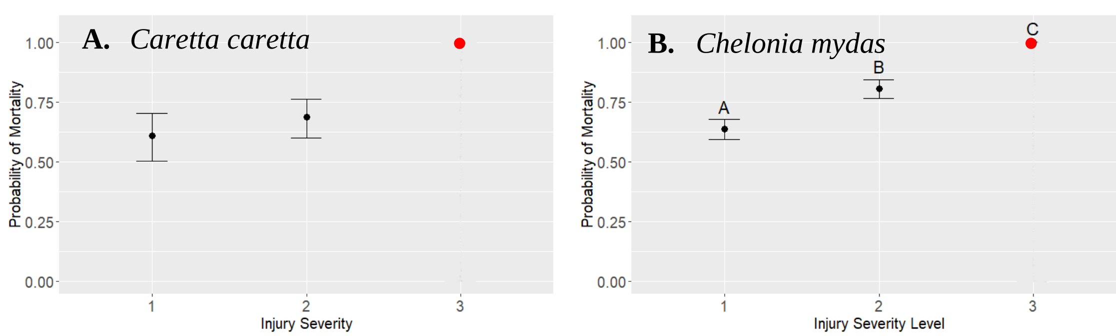

Figure 11. (A) Probability of mortality based on injury severity in stranded loggerheads (*Caretta caretta*) from Florida, USA. (B) Probability of mortality based on injury severity in stranded green turtles (*Chelonia mydas*) from Florida, USA. The solid black dot represents the mean and the whiskers on either side of the mean represents the 95% confidence interval. The red dot indicates that, no turtles with severity level 3 survived rehabilitation.

Table 11. Mortality of green sea turtles (*Chelonia mydas*) based on anatomic location injury prevalence. In parenthesis are the number of turtles impacted over the total number of turtles with the affected anatomic location.

Anatomic Location	Died	Survived to be released
Head injury present	77.6% (38/49)	22.4% (11/49)
Medial carapace injury present	73.4% (141/192)	26.6% (51/192)
Lateral carapace injury present	76.4% (162/212)	23.6% (50/212)
Extremity injury present	81.8% (9/11)	18.2% (2/11)
Plastron injury present	82.4% (14/17)	17.6% (3/17)

DISCUSSION

Sea turtles face numerous anthropogenic threats, which can be quantified using stranding data from Florida, USA (Foley et al., 2017), and from other studies across the globe (Kopsida et al., 2002, Hazel & Gyuriz, 2006, Tomas et al., 2008, Casale et al., 2010; Orós et al., 2016; Shimada et al., 2017; Archibald & James, 2018). The data collected from nesting loggerheads for this study supplement our current understanding of anthropogenic and natural injury prevalence by observing turtles that were injured but did not strand. This project also evaluated sea turtles that stranded alive and entered rehabilitation facilities in Florida, USA.

INJURY PREVALENCE IN NESTING FEMALES

In Florida, boat strikes are the most common cause of death in loggerhead sea turtles, accounting for one-third of strandings from 1980–2014 (Foley et al., 2017; Foley et al., 2019); therefore, it was expected that nesting loggerhead turtles on Juno and Jupiter Beaches would have a higher prevalence of anthropogenic injuries compared to non-anthropogenic injuries. Approximately 82% of injuries on nesting loggerheads included in this study were anthropogenic (e.g., hook, entanglement, boat), with the most prevalent injuries due to boat strikes. In total, 10% of loggerheads on Juno and Jupiter Beaches had boat-related injuries, accounting for ~68% of all injuries recorded (excluding injuries from unknown sources). Consequently, boat interactions may be a more common occurrence and threat than initially perceived from stranding data alone.

Our results were similar to injury data collected from leatherback sea turtles in the northwest Atlantic Ocean, where anthropogenic injuries were significantly more abundant than predatory injuries; however, entanglement and hook injuries were more common in leatherbacks compared to boat strike injuries (Archibald & James, 2018). Leatherback turtles in the northwest Atlantic Ocean likely show dissimilarities in injury type and prevalence due to differences in behavior, diet, migratory patterns, nesting locations, dive duration/interval, and study sites. Leatherbacks are particularly vulnerable to entanglement incidents in the northern Atlantic coastal and shelf waters where fishery interactions are a major threat (James et al., 2008). Loggerheads, on the other hand, return to nearshore foraging habitats as subadults (Thomson et al., 2012; Ceriani et al., 2017), which have higher boat traffic, increasing their chances of interactions with boats (Thomson et al., 2012). These differences in foraging locations affect the kinds of threats faced by each species. Visual field and feeding behavior differences between leatherbacks and loggerheads influence how the same threat can impact the species differently. Loggerhead sea turtles have more accurate target biting, which results in greater hooking in the mouth, throat, and stomach, compared to leatherbacks, which have greater external hook punctures when interacting with longline fisheries (Epperly et al., 2012; Coelho et al., 2015; Warraich et al., 2020). The loggerheads assessed in our study followed similar patterns to historical stranding data (Foley et al., 2017), with boat injuries being the greatest injury found in both stranded and nesting loggerheads. Our data and stranding data indicate that boat strikes are a major threat to nesting loggerheads on Juno and Jupiter Beaches, Florida, USA.

It is unlikely that the nesting loggerheads assessed in this study had previously stranded, since none of the turtles, except one with no injuries, had been previously flipper or PIT tagged. It is unknown why some sea turtles never strand as a result of being wounded, but factors including severity, location, and size are likely reasons. According to the rehabilitation data collected for this study (discussed below), injury severity plays a significant role in mortality, with less severe injuries resulting in lower mortality. Additionally, a turtle's maturity status and size may affect its ability to survive boat interactions. Adult turtles may also be able to better fight secondary infections due to a more mature immune system (Coico et al., 2003; Keller et al., 2006; Zimmerman et al., 2010). An increased immune response could potentially explain why some turtles may survive certain threats without veterinary intervention; however, immune function was not analyzed in this study.

Injuries of unknown source were typically smaller and present on the lateral carapace. Loggerhead hatchlings held together in captivity show aggression towards one another and often bite at each other's extremities, posterior carapace, and neck (Higgins, 2003). It is also possible that small fish and/or other predators may bite at hatchling sea turtles, resulting in small injuries that eventually heal. Thus, small, unidentifiable injuries on the flippers and lateral carapace of loggerheads in our study may be the result of conspecific aggression as hatchlings or predation. Injuries categorized in this study as "unknown" could have been caused by boats, predation, or fishery interactions. Therefore, some injury categories are likely underestimated since 43.7% of injuries on nesting loggerheads were unidentifiable. Additionally, over half (59.1%) of the injuries recorded in this study were present only on the lateral carapace and/or extremity. This may explain why these turtles survived these interactions, since lateral carapace and extremity injuries avoid the spinal column and major organs (Wyneken, 2001). More severe injuries are increasingly likely to result in stranding or death, which is supported by the FWC data analysis conducted here. Four nesting loggerheads were found with head injuries, all of which were hook injuries that caused minor damage to the maxilla. The fact that no large head injuries were documented on nesting loggerheads may be because survival in turtles with moderate to severe head injuries is low.

A previous analysis of stranded turtles in Florida, USA, determined that 23.7% of the turtles had co-morbid conditions that may have increased their likelihood of a boat interaction (Foley et al., 2019). It is unlikely that co-morbid conditions (e.g., fibropapillomatosis tumors, brevetoxin exposure, other injuries) caused the turtles in this study to be struck by a boat as none of the tagged turtles in this study had external tumors and red tide did not occur during our sampling season. One nesting loggerhead included in this study was entangled in fishing line and struck by a boat (healed). The entanglement injury was shallow and likely occurred after the boat strike injury, which was healed while the entanglement injury was fresh. Similar results were observed in loggerhead sea turtles stranding in Virginia, USA, where the majority of turtles that died from boat or fishery interactions were healthy prior to the injurious event (Barco et al., 2016).

Only two nesting turtles were identified with entanglement injuries. One had an indentation on each side of the lateral carapace, likely from an entanglement earlier in life that restricted growth, while the other turtle emerged from the surf physically entangled in fishing line (which was removed from the animal during oviposition). Prevalence of entanglement injuries are likely underestimated due to difficulty in detection, since fishery interactions do not always result in scarring (Peckham et al., 2008; Archibald & James, 2018). A large majority of the injuries (67/71, 94.4%) identified in nesting loggerheads in this study were healed, and it is likely that some healed injuries, especially on soft tissue, went undetected. Sea turtle wounds can take months to years to enter the last phase of healing (Mettee & Norton, 2017). Since scarring is not always present after a fishery interaction, and most injuries evaluated in this study were healed, it is possible that entanglement and other injuries on sandy, nesting loggerhead sea turtles examined at night, may be underestimated. Another possible source of injury underestimation is the fact that the plastron on nesting loggerheads could not be observed, limiting the ability to detect injuries affecting the ventral side of the turtle.

Turtles may acquire multiple injuries from different sources over time. For example, eight turtles from a population of green turtles in Malaysia each had new boat strike injuries during the seven-year duration of the study, with one turtle experiencing multiple boat strikes in just three years (Phu & Palaniappan, 2019). Additionally, a leatherback nesting in 2019 on Juno and Jupiter Beaches, Florida, USA, was hit twice by a boat during that nesting season alone (LMC, unpublished data). Loggerheads in our study had mostly healed injuries, but the frequency of injury occurrence was high at approximately 24%. LMC will continue to monitor nesting females on Juno and Jupiter Beaches, Florida, USA, annually, as this will allow for a larger data set and an opportunity to compare prevalence data from year to year. This annual monitoring also allows for already tagged turtles to be examined for new injuries. For example, a loggerhead tagged in 2018 has returned to Juno and Jupiter Beaches to nest in 2020 with a new, severe boat strike injury that was not present in 2018.

Despite increasing annual nest count data, loggerhead populations have had limited recovery in Florida and elsewhere (Ceriani et al., 2019). Further research on how injuries impact sea turtles is critical for their population growth. Archibald and James (2018) used a combination of in-water surveys and nesting beach monitoring to generate leatherback injury data. Conducting in-water assessments provides data on males and individuals in other size classes that do not come ashore to lay eggs. This approach would allow us to understand how different threats impact different life-stage classes of loggerheads. Life-stage class data show that fisheries bycatch is a main source of mortality for juvenile and adult loggerheads in the southwest and northwest Atlantic sub-populations, whereas eggs and hatchlings are largely impacted by habitat alteration, pollution, and predation (Bolten et al., 2011; Lopez-Mendilaharsu et al., 2020). Additionally, 4.6% of adults, 3.5% of subadults, and 1.1% of juvenile loggerheads entrained in the St. Lucie Nuclear Power Plant canal in Fort Pierce, Florida, USA, had boat strike injuries (Norem, 2005). This lower prevalence of boat strike injuries in smaller turtles suggests that: (1) larger turtles are likely better able to survive the boat interactions; and/or (2) different life-stage classes experience different threats depending on their geographic location (Bolten et al., 2011). Future studies should further evaluate how sea turtle survivorship varies according to life-stage class.

LOGGERHEADS

Loggerhead injury condition (e.g., fresh, partially healed, healed) was significantly related to both case outcome and mortality. For loggerheads entering rehabilitation facilities, the probability of mortality decreased as injury condition improved. Entry into a facility with immediate treatment of a fresh boat strike may help prevent infection and encourage healing; however, if an injury is too deep and has impacted organs, treatment is more difficult (Mettee & Norton, 2017). Turtles entering rehabilitation facilities may be more likely to survive if their boat strike injury is already healed and they strand for a different reason (e.g., emaciation, disease) compared to turtles receiving rehabilitative care for fresh boat strike wounds. On average, more loggerheads strand in Florida, USA, due to boat strike collisions (20.5%) than due to disease (14.5%; Foley et al., 2017).

As the number of injured anatomic locations increased, so did the probability of mortality. A turtle injured in two anatomic locations was approximately six times more likely to die in rehabilitation than a turtle with a single boat injury. The more anatomic locations impacted by a boat injury, the more likely that the turtle's medial carapace or head would be impacted. Fleming (2008) found that chances of recovery were best when chelonians (freshwater turtles and tortoises) had only a single fracture to the carapace that avoided the spine, whereby when multiple injuries were present and affected the spinal cord, mortality was higher (Fleming, 2008). Our data suggest that once an injury impacts four anatomic locations, the probability of mortality reaches over 95% in loggerheads. In such cases, rehabilitation facilities should strongly consider euthanasia due to the low likelihood of survival.

While no other statistically significant predictors of mortality were identified for loggerheads, the analyses presented here revealed similar trends in both loggerheads and green turtles, which showed significant results (discussed below). Loggerheads were on average 31 cm larger (SCL_{min}) than green turtles entering rehabilitation facilities in Florida, USA. Differences between species and average turtle size may also explain differences in the results as Baker et al. (2015) found that loggerheads were more likely to survive rehabilitation compared to greens, and that larger turtles had lower mortality rates.

GREEN TURTLES

For green turtles, there were significant differences in case outcome based on percent carapace injury area, whereby fewer turtles with larger injuries survived to be released. Green turtles with wider injuries were significantly less likely to be released and had higher instances of death and euthanasia. The probability of mortality increased as the average injury width to SCW ratio increased. These results suggest that larger injuries lead to a greater chance of mortality because they impact a larger surface area, increasing the chances of hitting vital internal organs and secondary infections. In humans, bloodstream infection was more likely as wound size resulting from burns increased (Weber et al., 2009). Additionally, stress in animals can result in immunosuppression, making them more vulnerable to infection (Vogelnest, 2008). Larger injuries also take longer to heal (Fleming, 2008), increasing the chances of further complications during the rehabilitation process (Baker et al., 2015). Freshwater turtles and tortoises had a higher probability of mortality when 30% or more of the carapace was missing due to fractures (Fleming, 2008). Turtles in our study did not exceed a percent carapace injury area greater than 11.1%, but our data, similarly to Fleming (2008), support that injury size is a significant factor in mortality in rehabilitation patients. Injury length was also a major factor in boat-related mortality in Florida manatees, with longer propeller wounds resulting in higher mortality (Beck et al., 1982). Fleming (2008), Beck et al. (1982), and data from our study, support that larger injuries increase the probability of mortality in organisms struck by motor vehicles. Larger injuries are also likely to be deeper and more severe, with severity significantly impacting case outcome and mortality in green turtles in our study. When the average injury width in our study reached just over half (0.54) of the SCW, mortality reached 90%. This may provide a good benchmark for rehabilitation facilities to use if they are in triage protocols for injured turtles. While injury width had a significant impact on the probability of mortality in green turtles, percent carapace injury area and injury length did not. This may be due to the fact that blunt force trauma can create large superficial injuries, whereas, slicing or piercing injuries that are smaller by area may be deeper. An example can be seen in Fig. 12A, which shows a green sea turtle with a larger average injury width to SCW ratio and smaller percent carapace injury area; this turtle was euthanized. In contrast, a different green turtle with a smaller average injury width to SCW ratio, but larger percent carapace injury area, was released after rehabilitative care (Fig. 12B).

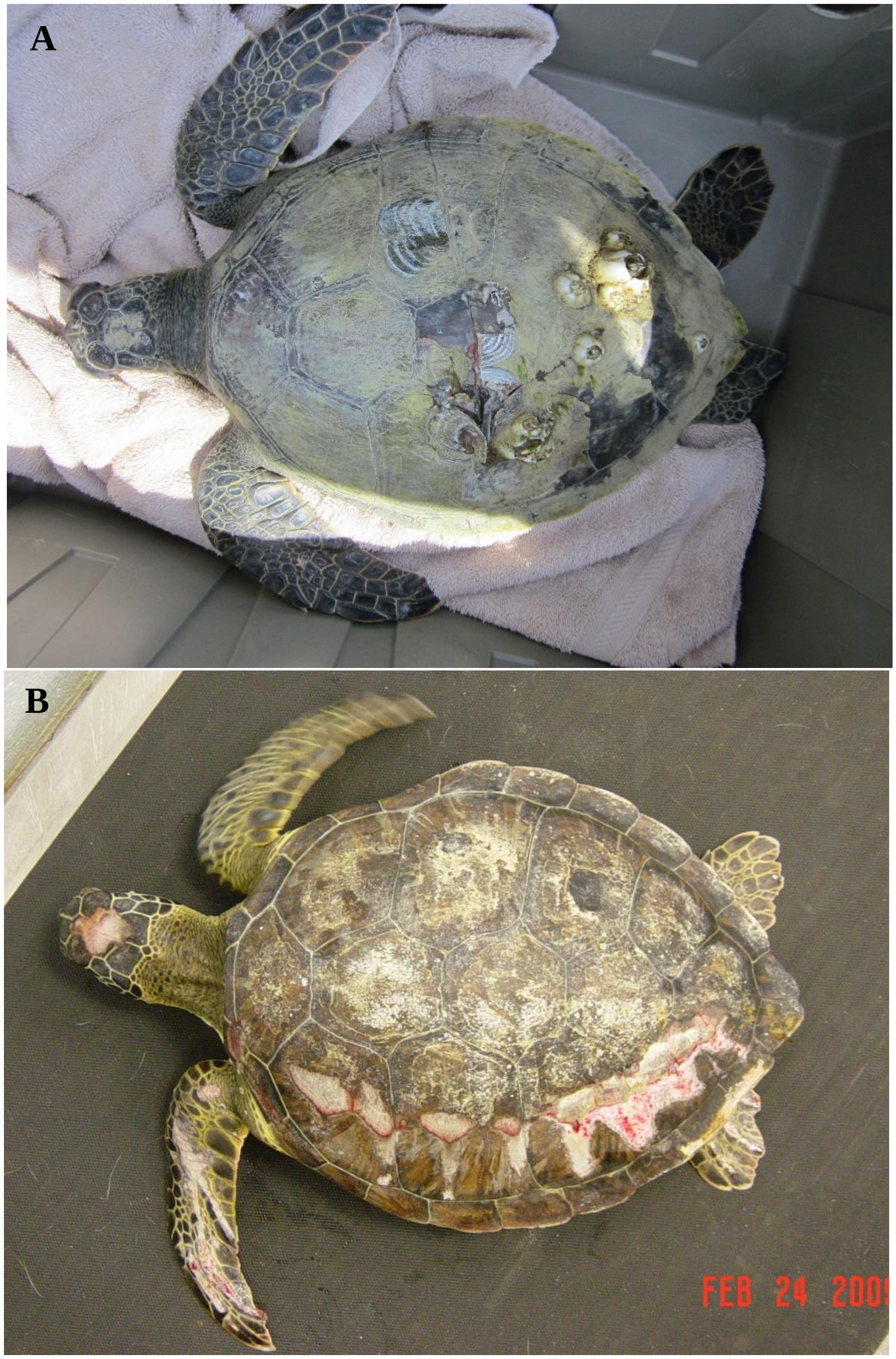

Figure 12. (A) A green turtle (*Chelonia mydas*) that entered a rehabilitation facility in Florida, USA, and was euthanized. The SCL_{min} was 28.1 cm, the percent carapace injury area was 1.8%, and the average injury width to SCW ratio was 0.27. (B) A green turtle (*Chelonia mydas*) that entered a rehabilitation facility in Florida, USA, and was later released. The SCL_{min} was 27.9 cm, the percent carapace injury area was 8.0%, and the average injury width to SCW ratio was 0.10.

Green turtles with lateral carapace injuries were more likely to die in rehabilitation. A study conducted on aquatic birds entering the International Bird Rescue in Los Angeles, California, USA, found a significant effect on case outcome based on the anatomic location of the most severe injury (Hanson et al., 2016). Birds with entanglement/hook injuries on the leg were more likely to be euthanized compared to birds with ingested line and injuries on the head, wings, or body (Hanson et al., 2016). Other studies on chelonians have also found that anatomic location influences mortality. For example, turtles and tortoises with injuries involving the head or spinal cord from automobile collisions had a higher probability of mortality (Fleming, 2008; Sack et al., 2017). A limitation to our analysis is that we only analyzed the presence of an injury in a specific anatomic location; this does not mean that the injury did not impact other anatomic locations (e.g., if an injury was present on the lateral carapace, it may also be present on the medial carapace). Noting where the most severe injury is located (similar to Hanson et al., 2016) may have been a better way to assess the effect of anatomic location on mortality. Our data show that regardless of anatomic location, the probability of turtles dying after entering rehabilitation facilities with boat strikes was high (>73% in all cases). Injury prevalence on the extremities ($N = 11$) and plastron ($N = 17$) was low, likely because boat strike injuries are less likely to impact these areas (Cecala et al., 2009; Foley et al., 2019). Low sample sizes in these two categories may explain why statistically significant trends in case outcome and mortality were not shown. The trauma caused by boats may be lethal regardless of the impacted location. Therefore, injury size and severity are likely better predictors of mortality.

Similar to loggerheads, green turtle injury condition (e.g., fresh, partially healed, healed) was significantly related to both case outcome and mortality. As injury condition improved, the probability of mortality decreased for green turtles. It is important to note that just because an animal with a healed injury survived the boat interaction, does not mean that similar fresh injuries in similar anatomic locations do not lead to mortality on other animals (Wells et al., 2008). Turtles entering rehabilitation facilities with old or partially healed injuries are recommended to be cleaned and monitored, but will likely continue to heal on their own (Wyneken et al., 2006). Turtles with fresh injuries may need more veterinary intervention, such as antimicrobial therapy and negative pressure wound therapy, which increases healing rate, helps remove bacteria and other contaminants, and increases blood flow (Thompson and Marks, 2007). These increased complications may explain why turtles with fresh injuries have a higher rate of mortality compared to turtles with healed injuries.

Injury severity also had a significant effect on case outcome and mortality for green turtles. As injury severity increased for green turtles, so did the probability of mortality. Injury and illness severity have been found to be significant predictors of mortality in wildlife rehabilitation for reptiles, birds, and mammals (Fleming, 2008; Kelly et al., 2011; Grogan & Kelly, 2013). Injuries penetrating the coelomic cavity in turtles with vehicular trauma increased the chances of mortality by 4.8 times, as this increases the chance of impacting internal organs (Sack et al., 2017). Infections of major wounds are more likely to result in the death of animals in rehabilitative care, as animals are usually better able to heal from minor injuries (Stocker, 2013). More severe injuries are more prone to high rates of infection, that in turn may be lethal. In our study, larger and deeper (entering the coelom) injuries were more severe; therefore, the severity data from our study support the hypothesis that larger injuries are more likely to result in mortality compared to smaller injuries. Turtles entering rehabilitation facilities with more severe injuries tend to die rapidly (Baker et al., 2015). Given the fact that all turtles in our study with an injury severity level of 3 died, it is recommended that rehabilitation facilities with limited resources euthanize any turtle with an injury severity level of 3, since their prognosis is likely grave. Since 71.4% (N = 15/21) of green turtles with an injury severity level of 3 were euthanized, it appears that rehabilitation facilities are already implementing this strategy.

It was hypothesized that stranding date, which was categorized into season (e.g., cold: December–April; hot: May–November), would have an impact on case outcome and mortality; with turtles stranding in cooler months having a higher probability of mortality, due to the potential for a weakened immune response (Saad & El Ridi, 1988; Saad et al., 1990). Our results demonstrate that season had no effect on the case outcome or mortality of green turtles entering rehabilitation facilities due to boat strikes. Cold-stun events in Florida, USA, are uncommon, with the last major event in January 2010 (Roberts et al., 2013). Although cold-stun events are rare, lower temperatures can still affect sea turtles' immune systems. This is because the immune response of reptiles (which are poikilothermic) is affected by temperature and season (Zapata et al., 1992; Keller et al., 2006), with reduced immune function often observed in some species during winter months (Saad & El Ridi, 1988; Saad et al., 1990) and increased immune function with warmer temperatures (Kluger et al., 1975). Boat strike strandings are generally higher in the spring and summer months (Kopsida et al., 2002, Casale et al., 2010), which may skew mortality proportions due to differences in sample size. However, this is unlikely the case in our study, because the turtles evaluated in our study had similar stranding numbers between the two season categories. With 175 turtles (133 green turtles, 42 loggerheads) stranding in the "hot" season and 143 turtles (121 green turtles, 22 loggerheads) stranding in the "cold" season. Incorporating sea surface temperature (SST) data would have been a more precise way to test this hypothesis and is a limitation to this analysis. However, the SST in December, January, February, March, and April are generally lower than the rest of the year in Florida, USA (He et al., 2003).

This study also did not find a significant effect on case outcome or mortality according to life-stage class or SCL_{min}. However, another study evaluating turtles that were admitted to rehabilitation facilities in Florida, USA, found that with increased body size, the probability of a successful release also increased (Baker et al., 2015). Larger turtles have more mature immune systems to better fight secondary infections from injuries (Coico et al., 2003; Keller et al., 2006; Zimmerman et al., 2010), which may explain their lower mortality in rehabilitation facilities. Larger turtles also have thicker scutes (López-Castro et al., 2014), which are better able to protect them from external injuries (Hu et al., 2011). Even though our study did not reveal a statistically significant relationship between SCL_{min} and mortality, there was a trend in both loggerheads and green turtles that as SCL_{min} increased the probability of mortality decreased, which may still have clinical relevance. Differences between our study and Baker et al. (2015) may be due to the fact that we specifically looked at boat strike injuries, whereas the Baker et al. (2015) evaluated all turtles that entered rehabilitation facilities regardless of cause.

Case outcome in rehabilitation facilities is usually related to the initial cause(s) of stranding. Turtles admitted to rehabilitation facilities due to entanglement in Gran Canaria Island, Spain and in Florida, USA, had a high success rate, with more than 90% of turtles being released (Orós et al., 2016; FWC Stranding Data, 2008–2017); however, turtles admitted to rehabilitation facilities with trauma from boat strikes have the worst prognosis for release compared to turtles with entanglement, hook, and shark attack injuries (Appendix B; Orós et al., 2016; FWC Stranding Data, 2008–2017). Our results for boat strike patients follow this trend, with only 27.3% of turtles struck by boats being released back into the wild. The fact that boat strike patients generally have a low likelihood of being released helps explain why some prognostic indicators (e.g., anatomic location) were statistically insignificant; injury severity, size, and condition are better indicators of mortality according to the results presented here. Traumatic boat strike injuries are often fatal due to the rapid loss of vital function (Stacy et al., 2017). Additionally, boat strike injuries are likely to be larger than entanglement, hook, and shark attack injuries, again leading to reduced survival in turtles hit by boats. With the high costs of rehabilitation (Baker et al., 2015), it is important for rehabilitation facilities to have quantitative data to make informative decisions for their turtle patients.

Boat strike injuries are the most fatal injury to sea turtles admitted to rehabilitation facilities. Larger and more severe boat strike injuries are more likely to result in sea turtle mortality. Rehabilitation facilities with limited resources need to streamline triage protocols in order to help the most individuals entering their facilities. Therefore, while animal welfare should always take precedence, veterinarians should give preference to turtles entering rehabilitation facilities with smaller, less severe injuries regardless of the anatomic location.

CONCLUSION

Most of the injuries found on nesting loggerheads in this study were classified as anthropogenic. Anthropogenic threats likely impact sea turtles to a greater extent than shown by this study alone. Based on an analysis of stranding data in Florida, boat strikes significantly contribute to loggerhead mortality (20.5%) (Foley et al., 2017). Data from rehabilitation facilities show that boat strikes are the most fatal injury to turtles, compared to other causes of admission. Turtles that are struck by boats and survive may still have abnormalities that prevent successful reproduction. For example, female diamondback terrapins (*Malaclemys terrapin*) with missing rear flippers may have difficulty in successfully digging a nest (Cecala et al., 2009) and male wood turtles (*Glyptemys insculpta*) with at least one missing limb are often unable to mate (Burger & Garber, 1995). Boat strike injuries can result in the loss of limbs or impact the spinal cord impairing limb function. A boat strike injury impacting the spinal cord of a nesting loggerhead has resulted in partial paralysis of her rear flippers, preventing her from successfully nesting, unless night-time surveyors dig her egg chamber (LMC, unpublished data). Body condition and the ability to avoid predators also decreases when limbs are missing due to reduced foraging success and reduced agility and speed (Cecala et al., 2009). Therefore, even if sea turtles survive the initial boat strike, subsequent problems may result that affect their reproductive ability and/or overall health. It is important for conservation and management initiatives to understand how different threats impact the entire population, beyond their contribution to mortality based on stranding data. Understanding that boat interactions affect a significant portion (~10%) of the nesting loggerhead population of Juno and Jupiter Beaches, Florida, USA, allows for better decision-making regarding conservation efforts such as boat speed restriction zones (voluntary and involuntary). The loggerhead recovery plan includes boat interactions as a major threat to the northwest Atlantic population (USFWS, 2008). Despite this, however, the 2019 progress assessment states that boat strikes have not yet been addressed in terms of loggerhead population recovery (Bolten et al., 2019). Multiple studies show the significant impact that boat interactions have on both stranded and wild-caught sea turtles, and therefore should be made a high priority in loggerhead population recovery plans.

Boating restrictions (speed-zones or no-entry zones) have been implemented for the protection of marine mammals in Florida, USA, and in other parts of the world. Voluntary boat restriction areas have been successful for the protection of the North Atlantic right whale on the Scotian shelf, due to boaters' willingness to comply (Vanderlaan & Taggart, 2009). There are limited open-water protections for the North Atlantic Right Whale in northeastern Florida, USA (from St. Augustine to Georgia), under 50 CFR § 224.105, which does enforce speed restrictions for vessels ≥65ft between November 15 to April 15 (Silber & Bettridge, 2012). This specific mandate would not be especially beneficial for migrating sea turtles as it only encompasses the northeastern region of Florida, USA (from St. Augustine to Georgia), and does not occur during most of the loggerhead nesting season in Florida, USA (April to September). The location in northeast Florida, USA, may provide some protection since it does overlap with a significant foraging ground for Florida adult loggerheads (Ceriani et al., 2017); however, turtles are less likely to be struck by boats when foraging (Foley et al., 2013). Manatee protection zones do not extend into the Atlantic Ocean or Gulf of Mexico and they primarily include lagoons, bays, and rivers that typically end at inlets into the ocean (FFWCC, 2019). These protections may overlap with some sea turtle habitats (lagoons can be developmental areas for immature loggerhead and green turtles) (Ehrhart et al., 2007); however, they likely fail to protect adult loggerheads, a life stage class which is especially important for population recovery (USFWS, 2008). Currently, there are no boating regulations in Florida, USA, state waters to protect sea turtles (FFWCC, 2019). Since migrating loggerheads are more likely to be found near the surface (compared to when they are on their foraging grounds) (Foley et al., 2013), implementing protections in the four loggerhead migratory corridors along the coast of Florida, USA (Foley et al., 2013), may provide an excellent strategy for reducing boat interactions with sea turtles. Loggerhead foraging locations in east central Florida, the continental shelf off west Florida, and the tip of the Florida Keys, USA (Ceriani et al., 2017), may be secondary areas to consider implementing boating restrictions where large aggregations of turtles can be found. The lethality of boat strike injuries to turtles admitted to rehabilitation facilities and the impact that boats have on the nesting loggerhead population (10% with boat strike injuries) in Juno and Jupiter Beaches, Florida, USA, warrants that further action is needed to remediate the issue.

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APPENDICES

APPENDIX A: Logistic regression model comparisons

Comparing models using average, total, minimum, and maximum injury lengths and widths for loggerheads (*Caretta caretta*).

Average injury length to SCL_{min} ratio, total injury length to SCL_{min} ratio, minimum injury length to SCL_{min} ratio, and maximum injury length to SCL_{min} ratio were strongly correlated (VIF > 12). Average injury width to SCW ratio, total injury width to SCW ratio, minimum injury width to SCW ratio, and maximum injury width to SCW ratio were also highly correlated (VIF > 11). Thus, four independent regression models for mortality were compared: one with all predictors except total, minimum, and maximum injury lengths and widths (e.g., SCL_{min}, carapace injury percent, average injury length to SCL_{min} ratio, average injury width to SCW ratio, number of injuries and number of injury locations); the second model with the same predictors, except the average injury length to SCL_{min} ratio was replaced with total injury length to SCL_{min} ratio and the average injury width to SCW ratio was replaced with total injury width to SCW ratio; the third model with the same predictors, except the total injury length to SCL_{min} ratio was replaced with minimum injury length to SCL_{min} ratio and the total injury width to SCW ratio was replaced with minimum injury width to SCW ratio; and the fourth model with the same predictors, except the minimum injury length to SCL_{min} ratio was replaced with maximum injury length to SCL_{min} ratio and the minimum injury width to SCW ratio was replaced with maximum injury width to SCW ratio. We used the Akaikie information criterion (AIC) to identify the best model.

The FULL MODEL was: model.all = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent + Average.Length.Ratio + Injury.length.SCL.ratio..Total. + LmaxRatio + LminRatio + Average.width.ratio + Injury.width.SCW.ratio..TOTAL. + WmaxRatio + WminRatio + MINSCL + Number.of.Injuries + X..of.Locations, data=data, family = binomial(link="logit"), na.action(na.omit))

Checking for variance inflation factors using “library(car)” in R we received:

vif(model.all)

Table A1. Variance inflation factor values when the logistic regression model for loggerheads (*Caretta caretta*) was run with all the predictor variables.

Carapace injury %	Avg. L Ratio	Total L Ratio	L_{max} Ratio	L_{min} Ratio	Avg. W Ratio	Total W Ratio	W_{max} Ratio	W_{min} Ratio	SCL_{min}	# of injuries	# of locations
5.5	674.9	12.3	161.1	225.9	397.5	11.0	116.9	134.1	1.4	9.7	2.0

The following four models were compared:

One using average injury length to SCL_{min} ratio and average injury width to SCW ratio:

```
> model.avg = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent +
Average.Length.Ratio + Average.width.ratio + MINSCL + Number.of.Injurie
s + X..of.Locations, data=CC, family = binomial(link="logit"), na.actio
n(na.omit))

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.32995   0.05073   0.40448   0.69236   1.28178

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)             -1.97501    3.98502  -0.496   0.6202
Carapace.injury.Percent -0.05627    0.18224  -0.309   0.7575
Average.Length.Ratio     3.89890    3.25151   1.199   0.2305
Average.width.ratio     -1.32418    3.07917  -0.430   0.6672
MINSCL                  -0.02878    0.03788  -0.760   0.4473
Number.of.Injuries       0.69015    0.44886   1.538   0.1242
X..of.Locations          1.79352    0.87639   2.046   0.0407 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 56.181  on 51  degrees of freedom
Residual deviance: 42.718  on 45  degrees of freedom
  (12 observations deleted due to missingness)
AIC: 56.718

Number of Fisher Scoring iterations: 6
```

One using total injury length to SCL_{min} ratio and total injury width to SCW ratio:

```
> model.total = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent
+ Injury.length.SCL.ratio..Total. + Injury.width.SCW.ratio..TOTAL. + MI
NSCL + Number.of.Injuries + X..of.Locations, data=CC, family = binomial
(link="logit"), na.action(na.omit))

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.21886   0.05858   0.45717   0.63050   1.32993

Coefficients:
                                Estimate Std. Error z value Pr(>|z|)
(Intercept)                      0.84672    3.35262   0.253    0.801
Carapace.injury.Percent          0.04819    0.21901   0.220    0.826
Injury.length.SCL.ratio..Total.  0.26847    2.28326   0.118    0.906
Injury.width.SCW.ratio..TOTAL.  -1.34297    1.66873  -0.805    0.421
MINSCL                          -0.04484    0.03747  -1.197    0.231
Number.of.Injuries               0.59530    0.44079   1.351    0.177
X..of.Locations                  1.43413    0.77132   1.859    0.063 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 56.181  on 51  degrees of freedom
Residual deviance: 44.103  on 45  degrees of freedom
  (12 observations deleted due to missingness)
AIC: 58.103
```

```
Number of Fisher Scoring iterations: 6
```

One using maximum injury length to SCL_{min} ratio and maximum injury width to SCW ratio:

```
> model.max = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent +
LmaxRatio + WmaxRatio + MINSCL + Number.of.Injuries + X..of.Locations,
data=CC, family = binomial(link="logit"), na.action(na.omit))

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.11966   0.04708   0.38820   0.66289   1.38588

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)              0.33084    3.83477   0.086    0.931
Carapace.injury.Percent  0.03740    0.22645   0.165    0.869
LmaxRatio                1.59847    2.94829   0.542    0.588
WmaxRatio               -3.71765    3.22071  -1.154    0.248
MINSCL                  -0.04552    0.03841  -1.185    0.236
Number.of.Injuries       0.48440    0.38606   1.255    0.210
X..of.Locations          1.92939    0.89965   2.145    0.032 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 56.181  on 51  degrees of freedom
Residual deviance: 42.305  on 45  degrees of freedom
  (12 observations deleted due to missingness)
AIC: 56.305

Number of Fisher Scoring iterations: 6
```

One using minimum injury length to SCL_{min} ratio and minimum injury width to SCW ratio:

```
> model.min = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent +
LminRatio + WminRatio + MINSCL + Number.of.Injuries + X..of.Locations,
data=CC,
family = binomial(link="logit"), na.action(na.omit))

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.34016   0.04039   0.38586   0.66832   1.38521

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)             -3.09154    3.99167  -0.774   0.4386
Carapace.injury.Percent -0.04605    0.16461  -0.280   0.7797
LminRatio                5.04134    3.21213   1.569   0.1165
WminRatio               -0.46886    2.78188  -0.169   0.8662
MINSCL                  -0.02264    0.03762  -0.602   0.5473
Number.of.Injuries       0.86115    0.48407   1.779   0.0752 .
X..of.Locations          1.81026    0.88646   2.042   0.0411 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)
```

```
    Null deviance: 56.181  on 51  degrees of freedom
Residual deviance: 42.042  on 45  degrees of freedom
  (12 observations deleted due to missingness)
AIC: 56.042

Number of Fisher Scoring iterations: 6
```

The model using maximum injury length to SCL_{min} ratio and maximum injury width to SCW ratio had the lowest AIC value, but the value was not much different from the model using average injury length to SCL_{min} ratio and average injury width to SCW ratio. The model using average injury length to SCL_{min} ratio and average injury width to SCW ratio had a lower AIC value compared to the model using total injury length to SCL_{min} ratio and total injury width to SCW ratio and was used in the following analysis to check for correlations.

vif(model.avg)

Table A2. Variance inflation factor values when the logistic regression model for loggerheads (*Caretta caretta*) was run using average injury length to SCL_{min} ratio and average injury width to SCW ratio.

Carapace injury %	Avg. L Ratio	Avg. W Ratio	SCL_{min}	# of injuries	# of locations
1.9	2.0	1.5	1.2	2.2	1.2

Comparing models using average, total, minimum, and maximum injury lengths and widths for green turtles (*Chelonia mydas*).

Average injury length to SCL_{min} ratio, total injury length to SCL_{min} ratio, minimum injury length to SCL_{min} ratio, and maximum injury length to SCL_{min} ratio were strongly correlated (VIF > 10). Average injury width to SCW ratio, total injury width to SCW ratio, minimum injury width to SCW ratio, and maximum injury width to SCW ratio were also highly correlated (VIF > 9). Thus, four independent regression models for mortality were compared: one with all predictors except total, minimum, and maximum injury lengths and widths (e.g., SCL_{min}, carapace injury percent, average injury length to SCL_{min} ratio, average injury width to SCW ratio, number of injuries and number of injury locations); the second model with the same predictors, except the average injury length to SCL_{min} ratio was replaced with total injury length to SCL_{min} ratio and the average injury width to SCW ratio was replaced with total injury width to SCW ratio; the third model with the same predictors, except the total injury length to SCL_{min} ratio was replaced with minimum injury length to SCL_{min} ratio and the total injury width to SCW ratio was replaced with minimum injury width to SCW ratio; and the fourth model with the same predictors, except the minimum injury length to SCL_{min} ratio was replaced with maximum injury length to SCL_{min} ratio and the minimum injury width to SCW ratio was replaced with maximum injury width to SCW ratio. We used the Akaikie information criterion (AIC) to identify the best model.

The FULL MODEL was: model.all = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent + Average.Length.Ratio + Injury.length.SCL.ratio..Total. + LmaxRatio + LminRatio + Average.width.ratio + Injury.width.SCW.ratio..TOTAL. + WmaxRatio + WminRatio + MINSCL + Number.of.Injuries + X..of.Locations, data=CM, family = binomial(link="logit"), na.action(na.omit))

Checking for variance inflation factors using "library(car)" in R we received:

vif(model.all)

Table A3. Variance inflation factor values when the logistic regression model for green turtles (*Chelonia mydas*) was run with all the predictor variables.

Carapace injury %	Avg. L Ratio	Total L Ratio	L_{max} Ratio	L_{min} Ratio	Avg. W Ratio	Total W Ratio	W_{max} Ratio	W_{min} Ratio	SCL_{min}	# of injuries	# of locations
3.0	222.2	10.2	48.2	76.2	65.9	9.9	20.6	18.9	1.2	7.5	1.5

The following four models were compared:

One using average injury length to SCL_{min} ratio and average injury width to SCW ratio:

```
> model.avg = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent +
Average.Length.Ratio + Average.width.ratio + MINSCL + Number.of.Injurie
s + X..of.Locations, data=CM, family = binomial(link="logit"), na.actio
n(na.omit))

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.4375  -0.1144   0.5783   0.7810   1.2713

Coefficients:
                         Estimate Std. Error z value Pr(>|z|)
(Intercept)             -0.284144   0.787350  -0.361  0.71818
Carapace.injury.Percent -0.150932   0.117372  -1.286  0.19847
Average.Length.Ratio     3.109564   1.591021   1.954  0.05065 .
Average.width.ratio      5.383189   1.791262   3.005  0.00265 **
MINSCL                  -0.013946   0.009557  -1.459  0.14450
Number.of.Injuries       0.040932   0.189163   0.216  0.82869
X..of.Locations          0.325069   0.298636   1.089  0.27637
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 247.43  on 219  degrees of freedom
Residual deviance: 224.03  on 213  degrees of freedom
  (34 observations deleted due to missingness)
AIC: 238.03

Number of Fisher Scoring iterations: 5
```

One using total injury length to SCL_{min} ratio and total injury width to SCW ratio:

```
> model.total = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent
+ Injury.length.SCL.ratio..Total. + Injury.width.SCW.ratio..TOTAL. + MI
NSCL + Number.of.Injuries + X..of.Locations, data=CM, family = binomial
(link="logit"), na.action(na.omit))

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.03888   0.06444   0.62819   0.75459   1.42743

Coefficients:
                                 Estimate Std. Error z value Pr(>|z|)
(Intercept)                      0.726791   0.685421   1.060   0.2890
Carapace.injury.Percent         -0.026642   0.127625  -0.209   0.8346
Injury.length.SCL.ratio..Total.  0.541538   0.964398   0.562   0.5744
Injury.width.SCW.ratio..TOTAL.   1.560351   0.908979   1.717   0.0861 .
MINSCL                          -0.012093   0.009363  -1.292   0.1965
Number.of.Injuries              -0.449768   0.178929  -2.514   0.0119 *
X..of.Locations                  0.601490   0.290175   2.073   0.0382 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 247.43  on 219  degrees of freedom
Residual deviance: 232.36  on 213  degrees of freedom
  (34 observations deleted due to missingness)
AIC: 246.36

Number of Fisher Scoring iterations: 4
```

One using maximum injury length to SCL_{min} ratio and maximum injury width to SCW ratio:

```
> model.max = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent +
LmaxRatio + WmaxRatio + MINSCL + Number.of.Injuries + X..of.Locations,
data=CM, family = binomial(link="logit"), na.action(na.omit))

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.44002  -0.07006   0.59383   0.77690   1.54923

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)             -0.03263    0.74341  -0.044  0.96499
Carapace.injury.Percent -0.15932    0.12376  -1.287  0.19800
LmaxRatio                2.50377    1.34359   1.863  0.06239 .
WmaxRatio                4.25561    1.53384   2.774  0.00553 **
MINSCL                  -0.01141    0.00948  -1.204  0.22867
Number.of.Injuries      -0.18933    0.15761  -1.201  0.22965
X..of.Locations          0.40604    0.29408   1.381  0.16737
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 247.43  on 219  degrees of freedom
Residual deviance: 226.20  on 213  degrees of freedom
  (34 observations deleted due to missingness)
AIC: 240.2
```

```
Number of Fisher Scoring iterations: 4
```

One using minimum injury length to SCL_{min} ratio and minimum injury width to SCW ratio:

```
> model.min = glm(Died..1..or.Survived..0. ~ Carapace.injury.Percent +
LminRatio + WminRatio + MINSCL + Number.of.Injuries + X..of.Locations,
data=CM,
family = binomial(link="logit"), na.action(na.omit))

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.4061  -0.0896   0.5904   0.8047   1.2752

Coefficients:
                         Estimate Std. Error z value Pr(>|z|)
(Intercept)              0.125039   0.757495   0.165    0.869
Carapace.injury.Percent -0.020086   0.099782  -0.201    0.840
LminRatio                1.425699   1.345582   1.060    0.289
WminRatio                4.044703   1.570188   2.576    0.010 **
MINSCL                  -0.015062   0.009512  -1.583    0.113
Number.of.Injuries       0.032302   0.204977   0.158    0.875
X..of.Locations          0.406635   0.298262   1.363    0.173
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 247.43  on 219  degrees of freedom
Residual deviance: 227.54  on 213  degrees of freedom
  (34 observations deleted due to missingness)
AIC: 241.54

Number of Fisher Scoring iterations: 5
```

The model using average injury length to SCL_{min} ratio and average injury width to SCW ratio had a lower AIC value compared to the model using total injury length to SCL_{min} ratio and total injury width to SCW ratio and was used in the following analysis to check for correlations.

vif(model.avg)

Table A4. Variance inflation factor values when the logistic regression model for loggerheads (*Caretta caretta*) was run using average injury length to SCL_{min} ratio and average injury width to SCW ratio.

Carapace injury %	Avg. L Ratio	Avg. W Ratio	SCL_{min}	# of injuries	# of locations
2.2	1.7	1.6	1.1	2.2	1.3

The model using average injury length to SCL_{min} ratio and average injury width to SCW ratio had the lowest AIC value for green turtles. When loggerhead turtles were analyzed separately the model with maximum injury length to SCL_{min} ratio and maximum injury width to SCW ratio had the lowest AIC value, but since the AIC value was not much different from the average injury length and average injury width model, and in order to keep consistency to be able to compare between the two species, the average injury length and width model was used for both species. Therefore, average injury length to SCL_{min} ratios and average injury width to SCW ratios were used throughout the results.

APPENDIX B: Extra table

Table B1. Case outcomes of loggerhead (*Caretta caretta* = CC) and green (*Chelonia mydas* = CM) sea turtles admitted to rehabilitation facilities.

Cause of Admission	Euthanized	Died	Released	Species	Citation
Entanglement (*N* = 919)	2.3%	5.3%	92.4%	CC	Orós et al., 2016
Hook/Line (*N* = 207)	3.4%	17.4%	79.2%	CC	Orós et al., 2016
Boat Trauma (*N* = 75)	18.7%	30.7%	50.7%	CC	Orós et al., 2016
Disease (*N* = 102)	5.9%	25.5%	60.6%	CC	Orós et al., 2016
Fibropapillomatosis (*N* = 756)	37%	37%	25%	CM	Page-Karjian et al., 2019
Shark (*N* = 91)	16.5%	41.8%	41.8%	CC & CM	FWC Stranding Data, 2008–2017
Entanglement (*N* = 453)	19.7%	22.3%	58.1%	CC & CM	FWC Stranding Data, 2008–2017
Hook/Line (*N* = 197)	7.6%	1.5%	90.9%	CC & CM	FWC Stranding Data, 2008–2017
Boat Trauma (*N* = 357)	51.5%	25.5%	23.0%	CC & CM	FWC Stranding Data, 2008–2017
Boat Trauma (*N* = 315)	35.6%	37.1%	27.3%	CC & CM	This Study