



Vessel avoidance behavior in green turtles off the west coast of Florida

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ABSTRACT: Vessel strikes are an increasing source of mortality for sea turtles in coastal waters with high recreational vessel traffic. We quantified flight initiation distance (FID) and avoidance behavior of green turtles *Chelonia mydas* in response to an approaching vessel traveling at different speeds in shallow coastal waters of Florida. Observational boat surveys were conducted at 3 vessel speeds, and observed FID was evaluated in relation to vessel speed, turtle size class (<60 cm vs. ≥60 cm estimated carapace length), and environmental conditions using a regression tree analysis. Observed FID was most strongly partitioned by vessel speed, with shorter mean distances consistently associated with higher speeds. Mean observed FID ranged from approximately 7.7 m at low vessel speed under specific environmental conditions to approximately 5 m or less at higher speeds. Turtle size class was not associated with differences in observed FID. Flight behavior was non-random, with turtles most frequently fleeing directly away from the vessel's trajectory, and was independent of vessel speed and turtle size. Observed FID reflects the combined effects of turtle behavior and observer detection. Nevertheless, the consistent association between higher vessel speed and reduced observed FID supports management strategies that would reduce boat speeds and increase boater awareness to protect green turtles in shallow coastal habitats.

KEY WORDS: Flight initiation distance · Vessel interactions · Green turtles · Boat speed · Observer detection · Conservation

1. INTRODUCTION

Collisions between marine wildlife and vessels are a globally recognized conservation concern affecting a wide range of taxa, including marine mammals, large fishes, and sea turtles (Schoeman et al. 2020). Vessel strikes can result in severe injury or mortality and have been identified as a major management challenge in regions where vessel traffic overlaps with important wildlife habitats. For some species, including baleen whales and the Florida manatee *Trichechus manatus latirostris*, research linking vessel speed to collision risk has directly informed mitigation strategies such as speed restrictions and spatial management (Calleson & Frohlich 2007, Vanderlaan & Taggart 2007, Gende et al. 2011).

Sea turtles are particularly vulnerable to vessel strikes because they frequently occupy shallow

nearshore habitats that are heavily used by recreational vessels. In-water monitoring programs have documented frequent overlap between sea turtles and vessel traffic in Florida's coastal habitats, highlighting the relevance of vessel interactions as a conservation concern (Eaton et al. 2008). Vessel-related injuries and mortalities have been documented globally, including in the USA, the Mediterranean Sea, Australia, and the eastern Pacific (Hazel & Gyuris 2006, Hazel et al. 2007, Casale et al. 2010, Denkinger et al. 2013, Barco et al. 2016, Shimada et al. 2017, Foley et al. 2019). In Florida, vessel strikes account for a substantial proportion of anthropogenic sea turtle strandings (Foley et al. 2019). This risk is expected to increase as both sea turtle populations and vessel registrations continue to rise in the region (Lasala et al. 2023, Rhodes 2025). Florida provides important foraging and nest-

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ing habitat for green turtles, and population recovery in parts of the species' range has increased the likelihood of turtle–vessel overlap in coastal waters (Seminoff et al. 2015).

Previous studies have demonstrated that vessel speed influences collision risk and avoidance responses in marine wildlife, including green turtles, with higher speeds associated with increased strike probability and reduced opportunity for evasive behavior (Hazel et al. 2007, Vanderlaan & Taggart 2007, Shimada et al. 2017). However, much of this work has focused on adult turtles, deeper-water habitats, or areas with persistent high commercial vessel traffic. Less is known about avoidance behavior across multiple size classes in shallow coastal systems, where turtles may have limited options for vertical avoidance and recreational vessel activity can be highly seasonal.

Flight initiation distance (FID)—the distance at which an animal initiates avoidance behavior in response to an approaching threat—is widely used to quantify disturbance and risk in wildlife studies (Hodgson & Marsh 2007, Darby et al. 2022). In vessel-based surveys, observed FID represents a combined outcome of animal behavior and observer detection under specific environmental and operational conditions. Understanding how observed FID varies with vessel speed and environmental context is therefore important for interpreting turtle–vessel interactions and informing management decisions.

In this study, we quantified observed FID and flight behavior of green turtles encountered during controlled vessel transects conducted at different speeds in shallow coastal waters of Florida. Our objectives were to (1) evaluate how observed FID varies with vessel speed, turtle size class, and environmental conditions; (2) describe patterns in turtle flight behavior relative to vessel approach; and (3) discuss implications for understanding vessel–turtle interactions and potential mitigation strategies, while explicitly acknowledging the limitations imposed by observer detection.

2. MATERIALS AND METHODS

Fieldwork was conducted in shallow coastal waters off the west coast of Florida near Crystal River and Homosassa, Citrus County (Fig. 1). The approximately 10.5 km² study area consists primarily of seagrass habitat with maximum depths of approximately 2 m and relatively low levels of commercial vessel traffic. Recreational boating activity is seasonal, with peak use during spring and summer months.

The study area was divided into 36 grid cells, and 2 km transects were conducted perpendicular to shore from randomly selected grid-cell starting points. For each transect, vessel speed was randomly assigned to one of 3 levels: low (4 km h⁻¹), medium (9 km h⁻¹), or high (14 km h⁻¹). These speeds reflected commonly

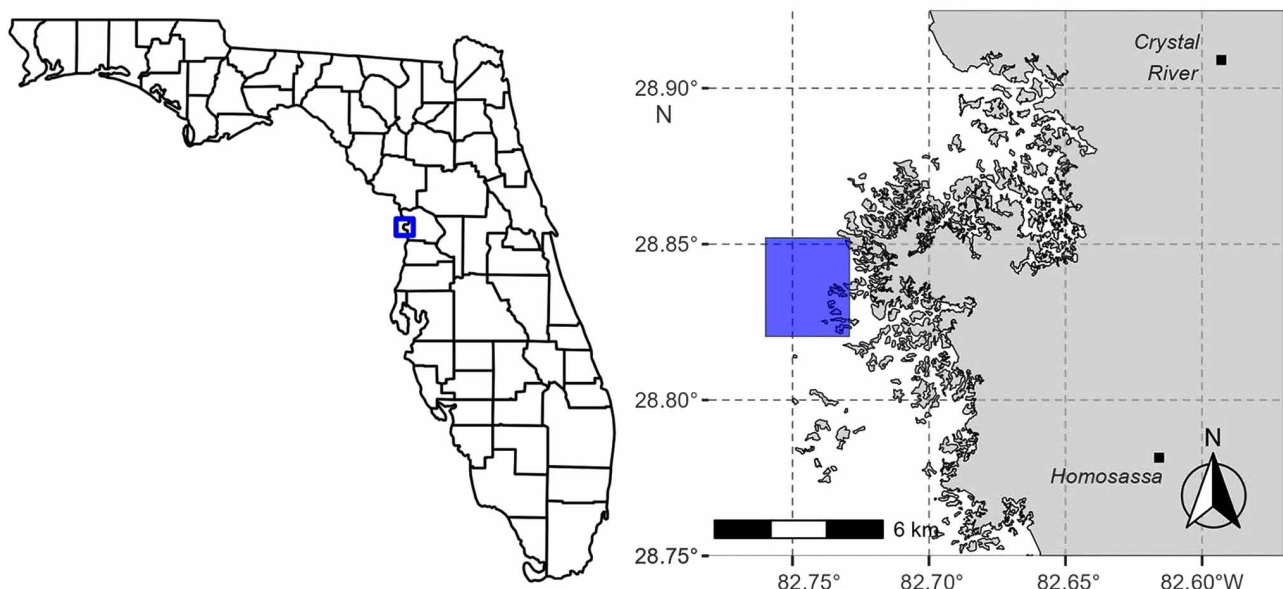


Fig. 1. Study area in Citrus County, Florida, USA, near Crystal River and Homosassa (Map created using R programming; R Core Team 2024). Blue box: the 10.5 km² study area, split into 0.25 km² grid cells ($n = 36$) for observational boat transects

observed recreational boating speeds in the area while allowing safe vessel operation and turtle avoidance. Transects were paused if another vessel crossed the transect line ahead of the survey vessel to minimize confounding effects.

Observational boat surveys were conducted from March through August of 2021 and 2022, coinciding with periods of high turtle presence and recreational vessel use in the region (Foley et al. 2019). Surveys were conducted from a 7.6 m Carolina Skiff, representative of the most common class of recreational vessels registered in Florida (Rhodes 2025). Surveys were conducted only under generally favorable visibility conditions (low wind and wave activity, minimal glare, and adequate water clarity) to maximize reliable turtle detection. Environmental variables recorded at the start of each transect included water depth, water clarity, wind speed and direction, cloud cover, sun angle and direction, tidal phase, moon phase, and engine noise. All recorded variables were considered candidate predictors during analysis.

Two trained observers were positioned at the bow of the vessel and scanned a forward field of view approximately 45° to either side of the bow (Fig. 2). A turtle was considered 'on transect' if detected ahead of the vessel within this field of view. Upon detection, observers visually estimated the distance from the vessel's bow at which the turtle initiated avoidance behavior, if any, and recorded the angle to the turtle using an inclinometer. This angle was later used to calculate FID via triangulation based on observer eye height above the water (Larjavaara & Muller-Landau 2013).

Size class was identified visually. Green turtles were classified as 'small' (<60 cm estimated carapace length) or 'large' (≥60 cm), corresponding approximately to neritic juveniles versus subadults and adults (Limpus & Chaloupka 1997). The presence of visible fibropapillomatosis tumors was recorded opportunistically but was not included in analyses due to the low number of affected individuals. To evaluate the reliability of visual distance estimates, visually estimated FID values were compared to calculated FID values derived from inclinometer measurements. As these measures did not differ significantly, visual estimates were used in subsequent analyses. Following detection, turtle flight behavior was categorized as fleeing away from the vessel's trajectory, fleeing parallel to the transect line, fleeing across the transect line, or exhibiting no observable flight response. These categories describe horizontal movement relative to

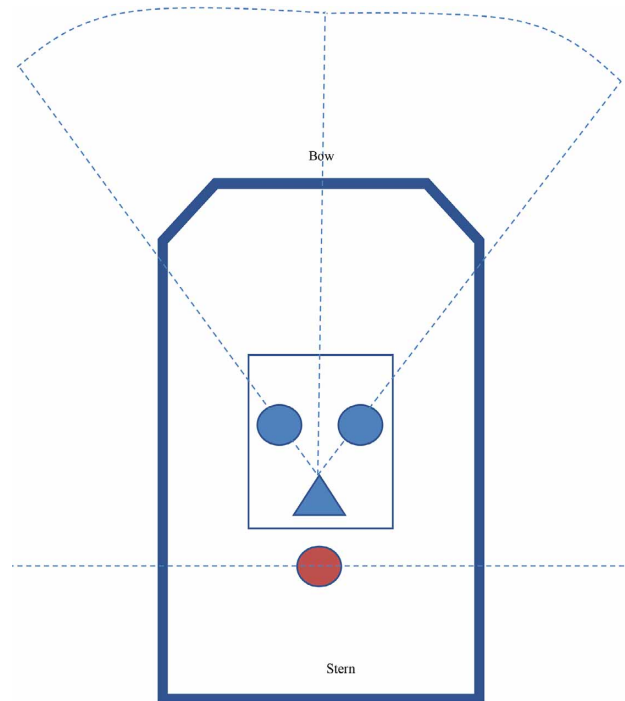


Fig. 2. Observers' orientations while conducting survey transects. Blue circles: turtle observers; blue triangle: boat captain; orange circle: data collector and boat monitor. 'On transect' was considered to be any turtle spotted in front of the vessel, in a field of vision approximately 45° off the port and starboard corners of the bow. Dashed lines represent the observers' line of sight and the boat monitors' line of sight

the vessel's path and do not distinguish among vertical avoidance responses.

All analyses were conducted in R (R Core Team 2024). To examine how observed FID varied with vessel speed, turtle size class, and environmental conditions, we used a regression tree analysis implemented with the 'rpart' package (Milborrow 2011, Therneau et al. 2018). Regression trees iteratively partition data into groups with different mean response values based on predictor variables and are well suited for exploring non-linear relationships and interactions. All recorded predictors were initially included as candidate variables. The tree was subsequently pruned using cost-complexity criteria to reduce overfitting, resulting in a final tree that retained only variables that improved partitioning of observed FID. Regression trees identify variables and thresholds that best divide observed FID into groups; they do not provide formal hypothesis tests or establish causality.

Flight behavior frequencies were analyzed using chi-squared tests to assess whether behavior categories were randomly distributed and whether behavior was associated with vessel speed or turtle size class.

3. RESULTS

Across 76 transects conducted over 2 field seasons, we detected 96 turtles on transect, including 78 green turtles, 11 loggerhead turtles *Caretta caretta*, and 5 Kemp's ridley turtles *Lepidochelys kempii*. Analyses focused on green turtles due to sample size. Of the green turtles observed, 61 were classified as small (<60 cm) and 17 as large (≥ 60 cm).

The regression tree analysis identified vessel speed as the primary variable partitioning observed FID, with subsequent splits involving water depth, wind direction, sun angle, and cloud cover. Turtle size class did not appear in the final pruned tree (Fig. 3). Mean observed FID varied across terminal nodes of the tree, reflecting combinations of vessel speed and environmental conditions. For example, turtles encountered at low vessel speed (4 km h^{-1}) under a specific set of environmental conditions identified by the tree had mean observed FIDs of approximately $7.7 \pm 2.9 \text{ m}$, whereas turtles encountered at higher speeds ($9\text{--}14 \text{ km h}^{-1}$) often exhibited mean observed FIDs of approximately 5 m or less, depending on depth and cloud cover. Across the tree, branches associated with higher vessel speeds consistently exhibited lower mean observed FID than those associated with low speed. The total range of observed FID values spanned from 0 m (no observable flight response) to 15 m . Comparison of visually estimated and calculated FID showed no significant difference between methods (mean difference = 0.76 m , Student's *t*-test: $t = 1.62$, $df = 137.82$, $p = 0.11$), supporting the use of visual estimates in subsequent analyses.

Flight behavior was not randomly distributed across categories (chi-squared test: $\chi^2 = 30.205$, $df = 3$, $p < 0.001$). Green turtles most frequently fled directly away from the vessel's trajectory, followed by fleeing across or parallel to the transect line, with no-flight responses occurring least often (Fig. 4). Flight behavior was independent of vessel speed and turtle size class (chi-squared test: $\chi^2 = 8.9082$, $df = 6$, $p = 0.1788$ and $\chi^2 = 3.1975$, $df = 3$, $p = 0.3622$, respectively).

4. DISCUSSION

Observed FID of green turtles in this study was consistently shorter at higher vessel speeds, a pattern that aligns with previous work linking vessel speed to increased collision risk and reduced opportunity for avoidance in marine wildlife (Calleson & Frohlich 2007, Hazel et al. 2007, Vanderlaan & Taggart 2007). Across the range of environmental contexts identified by the regression tree, higher vessel speeds were associated with reduced mean observed FID, suggesting that increased speed narrows the margin for successful avoidance in shallow coastal habitats.

It is important to note that observed FID reflects a combined outcome of turtle behavior and observer detection under specific operational and environmental conditions. Even though surveys were conducted under generally favorable visibility, environmental variables retained in the regression tree—including water depth, cloud cover, sun angle, and wind direction—likely influence both turtles' per-

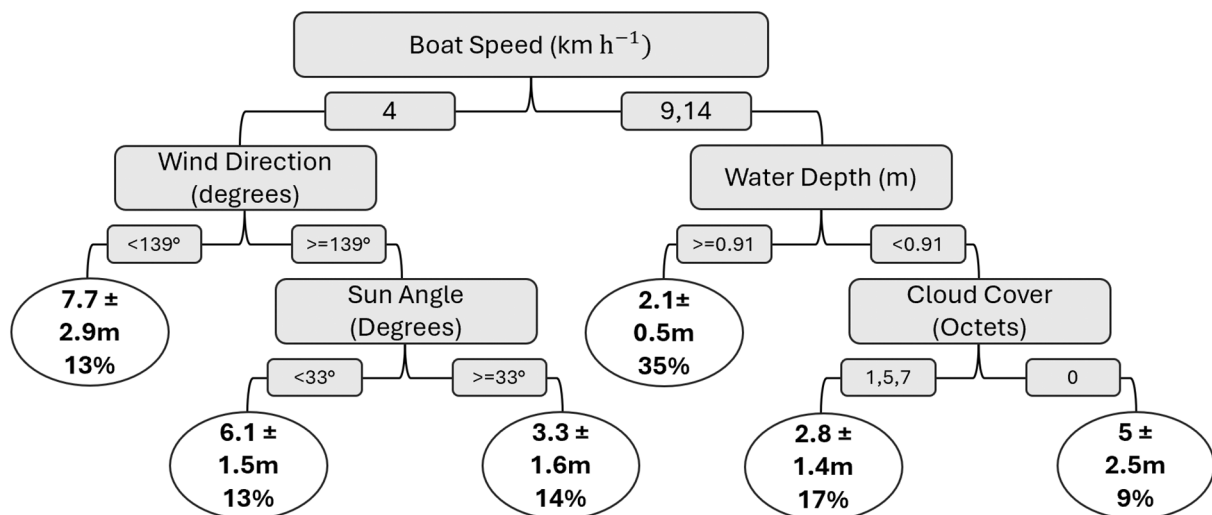


Fig. 3. Regression tree analysis for green turtle flight initiation distance. Numbers in **bold** represent the expected mean flight initiation distance of each subgroup and the percentage of the sampled population represented

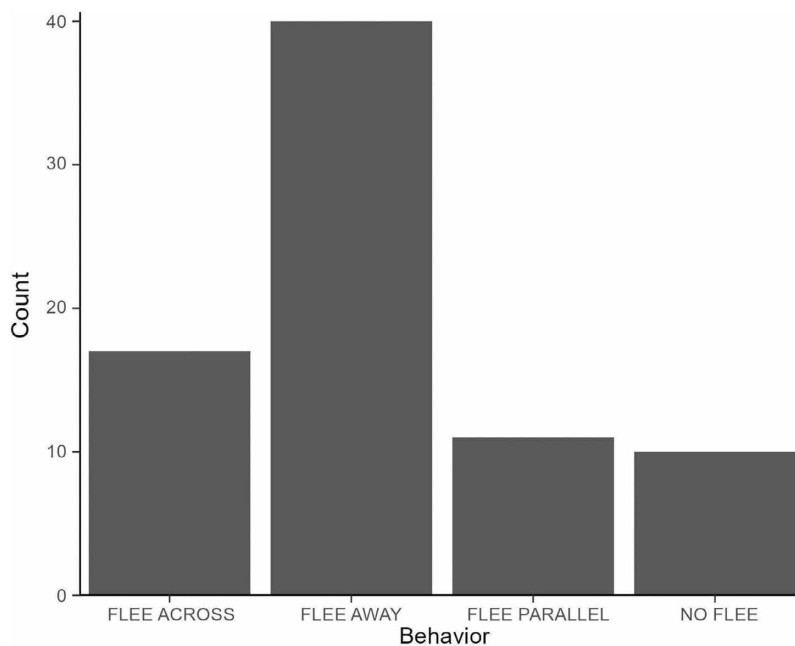


Fig. 4. Green turtle flight behavior for each observation. Directions 'across', 'away', and 'parallel' are in relation to the transect line (see Fig. 2). Flight behavior was not randomly distributed across categories ($\chi^2 = 30.205$, $df = 3$, $p < 0.001$) and independent of vessel speed and turtle size class ($\chi^2 = 8.9082$, $df = 6$, $p = 0.1788$ and $\chi^2 = 3.1975$, $df = 3$, $p = 0.3622$, respectively)

ception of an approaching vessel and observers' ability to detect turtles and their responses (Pirhalla et al. 2017, Darby et al. 2022). In addition, higher vessel speeds reduce the time available for observers to detect turtles at a given distance, which may bias observed FID downward even if turtles initiate avoidance at similar distances. Accordingly, variables selected by the regression tree should be interpreted as factors that partition observed FID rather than as definitive drivers of turtle decision-making.

Despite these limitations, the consistent association between vessel speed and reduced observed FID suggests that speed plays a central role in shaping encounter outcomes in shallow coastal systems. Florida provides important foraging and developmental habitat for green turtles, and population recovery in parts of the species' range has increased the likelihood of interactions between turtles and recreational vessels in coastal waters (Seminoff et al. 2015). Shallow seagrass habitats used by foraging green turtles are also areas of high recreational vessel use, increasing the probability of turtle–vessel encounters (Foley et al. 2019, Welsh & Witherington 2023).

Turtle size class did not influence observed FID or flight behavior, indicating that both smaller neritic turtles and larger individuals exhibited similar avoidance responses under the conditions observed. This

suggests that vulnerability to vessel encounters in shallow habitats is not restricted to a particular size class. Vessel strikes have been shown to cause mortality in otherwise healthy sea turtles, underscoring their potential to affect population dynamics even in recovering populations (Barco et al. 2016). As a result, interactions involving juveniles and subadults may represent an underappreciated source of risk in coastal foraging areas.

Flight behavior was non-random, with turtles most frequently fleeing directly away from the vessel's trajectory. This response likely minimizes collision risk when sufficient distance is available, as perpendicular movement away from the vessel path increases separation. However, shorter observed FID at higher vessel speeds may constrain the effectiveness of this avoidance strategy by limiting the time available for turtles to respond. Recreational boating activity has been shown to alter sea turtle behavior and

space use in coastal seagrass habitats, increasing the likelihood of turtle–vessel interactions in these areas (Wildermann et al. 2020). Together with the present findings, this highlights the importance of considering both vessel operation and habitat use when assessing collision risk.

From a management perspective, these results support reduced-speed measures and boater awareness initiatives in shallow coastal habitats with high densities of green turtles. Similar approaches have successfully reduced collision risk for other marine species, including manatees and large whales (Calleson & Frohlich 2007, Gende et al. 2011, Shimada et al. 2017, Fuentes et al. 2021). Even modest reductions in vessel speed may increase the distance and time available for both turtles and vessel operators to detect one another and respond appropriately. Future studies that explicitly quantify detection distance or detection lag would further strengthen inference about behavioral thresholds and refine understanding of turtle–vessel interactions in shallow coastal systems.

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