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Mapping the Exposure of Pantropical Spotted Dolphins and Common Bottlenose Dolphins to Different Categories of Vessel Traffic in Maui Nui, Hawai'i

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Abstract

The increase and diversification of vessel traffic worldwide has resulted in a variety of known disturbances to dolphins. As a remote island chain, the Hawaiian Islands rely heavily on the marine environment for transportation, recreation, and fishing that aggregates into significant levels of vessel traffic. Given the known presence of dolphins in this region, there is a gap in knowledge regarding the relative exposure risk that vessel traffic poses to island-associated dolphin populations in Hawai'i. This research identified the spatial distribution of pantropical spotted dolphins (*Stenella attenuata*) and common bottlenose dolphins (*Tursiops truncatus*) and determined the extent of their overlap with various categories of vessel traffic in Maui Nui, Hawai'i. Species distribution was determined using kernel density estimates based on sighting data from 50 spotted dolphin sightings and 75 bottlenose dolphin sightings collected from 2013 to 2018. A combination of vessel GPS and Automatic Identification Systems (AIS) vessel tracks were used to quantify vessel traffic within the study area, resulting in 22,464 vessel tracks that were subsequently compiled into categories for analysis from 2014 to 2017. Risk of vessel exposure between vessels and dolphins, or co-occurrence, was determined by calculating the product of predicted dolphin density and predicted vessel density. Both species were exposed to vessel traffic risk over 100% of their distribution, but their highest exposure risk varied spatially, with high risk defined as > 0.25 on a normalized scale of low (0) to high (1) risk. The highest vessel exposure risk for spotted dolphins occurred in deeper, offshore waters, while the highest risk for bottlenose dolphins was in shallow, coastal waters. The vessel categories with the largest area of high risk to spotted dolphins were tour vessel and commercial fishing vessel traffic, while commercial transportation traffic had the highest exposure risk for bottlenose dolphins. This article provides baseline information for understanding the vulnerability of two island-associated dolphin populations to the threat of vessel traffic and highlights the differences in relative exposure risk based on species and vessel categories.

Key Words: vessel traffic, pantropical spotted dolphin, *Stenella attenuata*, bottlenose dolphin, *Tursiops truncatus*, odontocete distribution, risk

Introduction

Vessel traffic is increasing worldwide (Hildebrand, 2009) and is considered a conservation threat in marine ecosystems due to underwater noise, pollution, and the potential for disturbance to and/or collisions with marine species, including dolphins (Halpern et al., 2015). The remote location of the Hawaiian archipelago results in heavy reliance on the marine environment for commercial transportation, and it provides year-round opportunities for various vessel-based activities such as marine wildlife viewing, snorkeling, leisure trips, fishing, and recreational boating. The Maui Nui region of Hawai'i is utilized by a large number of vessels of various types, including cruise ships and tankers that measure up to 317 m in length (Bureau of Ocean Energy Management [BOEM] & National Oceanic and Atmospheric Administration [NOAA], 2020). Vessel traffic can be perceived as a risk for dolphin species (Frid & Dill, 2002; Pirotta et al., 2015), and several studies have found that different vessel categories elicit varying responses from dolphins based on vessel speed as well as the movement patterns and predictability of the vessel route (Mattson et al., 2005; Baş et al., 2015). Additional vessel characteristics that may impact the behavioral response of dolphins include the number of vessels (Williams et al., 2002; Bejder et al., 2006), vessel type (Mattson et al., 2005; La Manna et al., 2013), and vessel approach method in close proximity to animals (Baş et al., 2015; Puszka et al., 2021). Previous research has documented various responses from common bottlenose dolphins (*Tursiops truncatus*) to vessel traffic based on vessel type, with slow-moving ships inciting little to no response, while fast boats with unpredictable movements, such as motorboats, dolphin-watching boats, high speed ferries, and jet skis, elicited negative behavioral reactions (Mattson et al., 2005; Baş et al., 2015). In the region of Maui Nui, marine vessel traffic has been found to pose a significant threat, impacting the fitness of humpback whales (*Megaptera novaeangliae*) by eliciting behavioral avoidance responses and causing injuries from vessel collisions (Lammers et al., 2013; Currie et al., 2021), and it may impact spinner dolphins (*Stenella longirostris longirostris*) in a similar manner (Stack et al., 2020; Self et al., 2021). However, the potential threats from vessel traffic have not been evaluated for other commonly observed dolphin species in the area.

Island-associated populations of dolphins have restricted movements and distributions (New et al., 2020). As such, there is a heightened need to understand the impact of human activities, such as vessel traffic, on the fitness of each population. In the Maui Nui region of Hawaiʻi, two commonly sighted island-associated populations of dolphins include pantropical spotted dolphins (*Stenella attenuata*) and common bottlenose dolphins (hereafter referred to as spotted dolphins and bottlenose dolphins). In the main Hawaiian Islands, spotted dolphins inhabit nearshore waters up to 5,000 m in depth (Baird et al., 2013), and genetic data indicate that there are separate populations associated with each island (Courbis et al., 2014; Carretta et al., 2020). Within this region, the last abundance estimate for the spotted dolphin 4-Islands stock was 4,283 animals in 2002 (Barlow, 2006), and there is currently insufficient data to assess and update population size and trends (Carretta et al., 2020). Photo-identification and genetic differentiation data have also established separate populations of bottlenose dolphins for each of the main Hawaiian Islands (Baird et al., 2009; Martien et al., 2012), where the populations demonstrate distinct habitat use in shallow, coastal waters (Baird et al., 2013). The most recent abundance estimate for bottlenose dolphins in Maui Nui determined the population to be 64 individuals (Van Cise et al., 2021). Recent work in Maui Nui has shown that the populations of spotted and bottlenose dolphins face anthropogenic threats from marine debris (Currie et al., 2017), fisheries (Baird & Webster, 2020; Carretta et al., 2020; Machernis et al., 2021), and disease (Carretta et al., 2020). However, there is a gap in knowledge regarding the level of vessel traffic exposure for these two island-associated populations and the potential associated threats.

The impacts of vessel presence on dolphins have been extensively studied globally and can range from short-term behavioral responses, such as changes in movement patterns and swim speeds (Mattson et al., 2005; Christiansen et al., 2010), to long-term displacement and avoidance of important habitats (Bejder et al., 2006; Lusseau et al., 2006) and injuries from vessel collisions (Schoeman et al., 2020). Furthermore, underwater vessel noise has resulted in disturbances to dolphins by altering acoustic signals (Guerra et al., 2014; Marley et al., 2017; Erbe et al., 2019), masking important communication (Pirotta et al., 2015) or interfering with echolocation that is used for navigation or locating prey (Nowacek et al., 2007). Research has shown that the level of disturbance to the impacted species may vary depending on life history patterns (Stack et al., 2020), social structure (Pirotta et al., 2014), sex (Lusseau, 2003a), and age class (Self et al., 2021) of animals. Short-term changes in an animal's energy budget as a result of disturbance can have long-term cumulative impacts that can lead to the reduction in the overall fitness of populations (Lusseau, 2003a; Bejder et al., 2006; New et al., 2020). As a result, disturbance from vessel presence should be evaluated on a population level for dolphin species.

To understand the impact of vessel interactions on dolphins, a current baseline of vessel traffic exposure must be established for dolphin populations. One method to evaluate the vulnerability of dolphin populations to vessel traffic exposure is to assess the "risk" or probability that an undesirable event will occur (Harwood, 2000). Several studies have described the risk vessels pose to dolphins by quantifying the spatial overlap, or co-occurrence, between the two (Williams & O'Hara, 2010; Morteo et al., 2012; Pirotta et al., 2018; Self et al., 2021). The co-occurrence of a particular species and a vessel is an important factor in determining vessel exposure risk (Williams & O'Hara, 2010); however, co-occurrence does not necessarily result in a collision or disturbance. Therefore, when calculating the relative vessel exposure risk, the results of this method indicate the risk of interaction, or spatial overlap (within 1 km^2 grid cell), between dolphins and vessels (Williams & O'Hara, 2010; Pirotta et al., 2018). As types of vessel traffic vary, with routes unevenly distributed throughout the marine environment (Schreier et al., 2007; Halpern et al., 2008), it is important to evaluate how different vessel types influence the relative exposure risk to dolphins. In this study, we examine the relative exposure risk to spotted and bottlenose dolphins from vessels by assessing dolphin distribution and relating it to vessel traffic within the Maui Nui region of Hawai‘i.

The main objectives of this research were (1) to provide baseline information regarding the relative exposure risk to spotted and bottlenose dolphins from vessel traffic, and (2) to identify areas within Maui Nui where relative exposure risk varies by vessel type. This information can be used to better understand how vessel traffic may impact these populations, providing resource managers with data to effectively protect and conserve these species in Maui Nui.

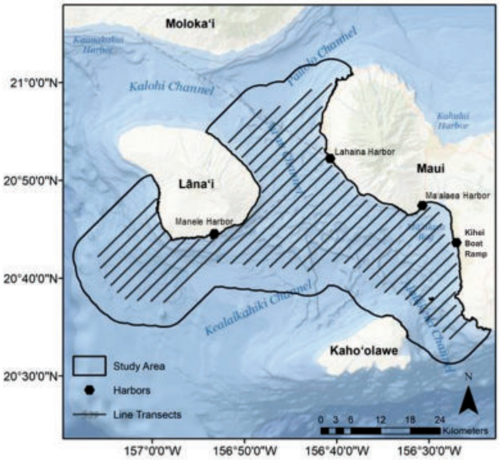

Figure 1. Map depicting the study area boundary, main harbor locations, and 32 transect lines for dolphin survey effort in Maui Nui, Hawai‘i, between 2013 and 2018.

Methods

Study Area and Survey Effort

Located within the leeward waters of the Maui Nui region of Hawai‘i, the study area consists of primarily nearshore waters enclosed by the four islands of Maui, Lāna‘i, Kaho‘olawe, and Moloka‘i. The study area covered 2,102 km^2 and is largely made up of shallow water channels, predominantly less than 200 m in depth, which were once land bridges connecting the islands (Grigg et al., 2002). However, some areas surveyed south of Lāna‘i reach depths over 600 m (Figure 1). Within the study area, high volumes of vessel-based activities occur each year with approximately 12,000 vessels registered in the state of Hawai‘i and approximately 1,413 registered in Maui County (Department of Boating and Ocean Recreation [DOBAR], 2020). In Maui County, registered marine vessels vary between 3.0 and 18.9 m in length, and utilize outboard, inboard, and water jet engines or wind sails for propulsion (DOBAR, 2020).

To capture the heterogeneity of dolphin distribution in the survey area, line-transect surveys were conducted from a 7.9-m dedicated research vessel between 7 February 2013 and 10 May 2018. Effort throughout the survey area was divided equally among 32 transects that began or ended at the 18-m depth contour and covered 637 km total. Each transect was oriented perpendicular to the depth contours and separated by 1 nmi. To increase dolphin detection probability, surveys were conducted only in optimal conditions when both Beaufort and Douglas Sea States were less than 4 (calm or light wind conditions with no white caps breaking). The starting transect and direction of survey were chosen randomly, and not all transects were completed during every survey. To achieve equal coverage throughout the survey area, effort varied by month and time of year, depending on weather conditions. During on-effort surveys, the captain and two observers continuously scanned the water with the naked eye for any dolphin species, while an additional crew member recorded data (Mann, 1999). Vessel presence was not recorded during dolphin survey effort. To minimize observer bias, all personnel were trained in data collection and at-sea observations, including dolphin species' identification and group size estimations. When a dolphin was sighted, a focal follow was initiated to confirm the species and to collect data on group size (number of animals—recorded as minimum, best, and maximum estimations), group composition (estimated number of adults, subadults, and calves), and photo-identification data. The location (latitude and longitude) of each sighting, or group of dolphins, was represented by a waypoint taken at the start of the sighting using a Garmin GPSMAP78 handheld Global Positioning System (GPS). Both on- and off-effort data were used in the subsequent analysis of spotted and bottlenose dolphin sightings. Off-effort scanning procedures and observation effort while traveling between transects and back and forth from the harbor were similar to on-effort, limiting any potential bias of using both sets of data in the analysis.

Dolphin Distribution

The GPS tracks from the research vessel surveys and the sighting locations for spotted and bottlenose dolphins were quality controlled for location errors and corrected or removed as applicable. Photo-identification data of both species were used to ensure that there were no same day resightings throughout the study period. The locations of all spotted and bottlenose dolphin sightings were imported into *ArcGIS*, Version 10.7 (Environmental Systems Research Institute [ESRI], 2019), using a WGS 1984 World Mercator projection and WGS 1984 datum. To determine the water depth at sighting locations, a grid characterized by water depth at a 50 m resolution, expressed in mean depth (m) from the Hawaiʻi Mapping Research Group (HMRG) Bathymetric Synthesis dataset, was utilized. The survey area was divided into 1 × 1 km grid cells based on the spatial resolution and accuracy of the available species and environmental data layers as seen in Stack et al. (2020) and Self et al. (2021). The total distance surveyed from both on- and off-effort tracks and sighting effort was determined per grid cell, and grid cells with no survey effort were dropped from subsequent analysis.

The density of spotted and bottlenose dolphins within the Maui Nui region was determined using the 'kernel interpolation with barriers' tool in *ArcGIS*, following the methods outlined in MacLeod (2013). This kernel density estimation method accounted for the influence of the islands in the study area as physical barriers to dolphin movement by measuring the shortest distance between each point without intersecting overland (MacLeod, 2013). To account for unequal survey effort and the possibility of multiple passes within the same grid cell during sighting effort, dolphin sightings of each species were weighted for survey effort, including on- and off-effort track lines. Greater weights were assigned to sightings in grids that received lower survey effort by dividing the number of sightings by the length of track line (km) surveyed within the same cell (sighting km^{-1}; Stack et al., 2020). The grid cell output size for the survey area was set to 1 × 1 km, and the bandwidth for spotted and bottlenose dolphin data was estimated at 5,320 m using the least-squares cross-validation selector (Bowman & Azzalini, 1997). The predicted kernel density estimates represent the number of sightings per km^2 that are likely to occur within each grid cell in the survey area, weighted for survey effort. The estimated area of each species' distribution was determined by summing the area of each grid cell for each kernel density map, and the percent area that each species distribution occupied within the study area was calculated by dividing the estimated area of species distribution by the total study area. Unequal sample sizes between the seasons (summer and winter) for dolphin surveys precluded further investigation into seasonal distribution of each species. It is important to note that the predicted density estimates for both species of dolphins are at the population level and represent the diurnal relative spatial distribution during the entire study period.

Vessel Traffic Data Compilation

Vessel traffic within the study area was quantified using a combination of vessel GPS and Automatic Identification Systems (AIS) vessel tracks. Vessel GPS tracks were obtained from 12 tour vessels that carry up to 120 passengers and range between 16.5 and 19.8 m in length, following the methods used in Currie et al. (2018). All vessel GPS tracks acquired were from trips departing from Maʻalaea and Lahaina harbors in Maui from 1 January 2014 to 31 December 2017. The AIS vessel traffic data were downloaded from Marine Cadastre for the years 2014 to 2017 to coincide with the available tour vessel GPS tracks (BOEM & NOAA, 2020). Data submission to AIS is required for all vessels over 300 gross tons and for passenger vessels that carry over 150 passengers; the downloaded data represented vessels between 9.8 and 317 m in length. Tracks from the 12 tour vessels were not duplicated in the AIS dataset as the tour vessels did not meet the requirements for mandatory submission and were not equipped with AIS transceivers. Vessel tracks were created from the AIS vessel data using the *ArcGIS Track Builder Pro*, Version 3.1, tool (downloaded from MarineCadastre.gov; BOEM & NOAA, 2020). The tool converts a single vessel's GPS points into a track line by connecting positions of a vessel with the same unique ship identifier data (Maritime Mobile Service Identity value) when positions were no more than 30 minutes apart and within 1 km of each other. Each track line created corresponded to a single vessel's trip route, and accumulated track lines from all vessel routes in the study area were used as a proxy for vessel traffic by year. All vessel tracks from AIS were subsequently compiled to represent general vessel traffic patterns for the study period (2014 to 2017) to match the timeframe of estimated dolphin densities; however, the results do not account for daily or hourly vessel traffic variations. There were brief periods throughout the study timeframe when data were not available from AIS; however, the pooling of data over the entire study period minimizes the impact of data gaps.

The data from both tour vessel GPS and AIS vessel track sources were quality controlled to eliminate any track locations outside the study area. All tour vessel GPS tracks and downloaded AIS vessel data that logged "vessel type code" data were sorted into the following vessel categories: all vessel traffic, commercial transportation vessels, recreational vessels, commercial fishing vessels, and tour vessels (Table 1). The number of unique vessel tracks available and the total distance (km) of each track was summed for each vessel category. The available tracks compiled for each vessel category is a minimum representation of vessel traffic throughout the study area as additional vessels that are not required

Table 1. Description of vessel type categories compiled from vessel Global Positioning System (GPS) tracks and Automatic Identification Systems (AIS) vessel data (BOEM & NOAA, 2020) in Maui Nui, Hawai'i, from 2014 to 2017.

Vessel type category	Vessel type description	Vessel type data source
All vessel traffic	All vessel track data in study area	All vessel GPS tracks and AIS vessel tracks from vessel type categories, including (1) the tracks in the categories below and (2) additional AIS vessel track data that do not have logged information for the vessel type code and "other" vessel type codes (i.e., School Ship, Unknown) that have unknown trip purposes and routes and did not fit into specified vessel type categories.
Commercial transportation vessels	Vessels used for movement of goods or people on a predetermined and predictable route going from port to port without deviating from the route in study area	AIS vessel type code data used: Tanker, Tug, Freight Ship, Public Freight, and Passenger (with an identifier of known ferries and cruise ships)
Recreational vessels	Vessels used for recreational purposes on an unpredictable or random route in study area	AIS vessel type code data used: Pleasure craft/sailing
Commercial fishing vessels	Vessels conducting commercial fishing on an unpredictable or random route in study area; this category represents only tracks and does not indicate active fishing activities.	AIS vessel type code data used: Fishing–commercial fishing vessel
Tour vessels	Vessels used for passenger trips with an unpredictable or random path in study area	All GPS vessel tracks and AIS vessel type code data used: Passenger (with an identifier of known tourism vessel's name)

to log information in AIS may depart from or transit through the area.

Vessel Traffic Density

In *ArcGIS*, the density of each vessel category was determined using the 'line density' tool, with a kernel density interpolation set with a grid cell output of 1 × 1 km. For the vessel traffic data, the bandwidth was selected using a least-squares cross-validation test (Bowman & Azzalini, 1997) and set to 5,320 m as was used in previous studies (Currie et al., 2017). Vessel density predictions used in this analysis represent the number of vessel tracks that are likely to pass through each grid cell in the survey area. Predicted vessel densities do not account for seasonal variations in vessel tracks but use the data to represent overall traffic patterns observed when vessel data were available during the period coinciding with dolphin surveys.

Relative Risk Exposure

To assess the relative exposure risk of dolphins to vessel traffic, the product of the weighted densities of each dolphin species and the density of vessel traffic for each vessel category was calculated for each grid cell (1 km^2). The resulting relative exposure risk estimates were characterized using a raster histogram distribution with a percent clip stretch function to reduce the effects of outliers in *ArcGIS*. The relative exposure risk estimates were normalized (from 0 to 1) using the equation: $(x-x_{min})/(x_{max}-x_{min})$, where x is the individual grid cell, x_{min} is the minimum raster value, and x_{max} is the maximum raster value (Stepanuk et al., 2018). Relative exposure risk maps represent areas of low (0) to high (1) risk for potential dolphin–vessel interactions. This approach quantifies the relative exposure risk (hereafter referred to as risk) for each dolphin species within their distribution. Results cannot be directly compared between species or vessel categories. For this analysis, raster grids with a risk value of > 0.25 were considered high (Merrick & Cole, 2007). To determine the area of high risk for each species and vessel category, the total number of raster grid cells with values > 0.25 were summed for each risk map. The percent of each species distribution that spatially overlapped with risk was determined by dividing the total grid area of risk (grid cell value > 0) by the total grid area for each dolphin species distribution.

Results

Survey Effort

The dolphin research surveys covered 38,962 km within the study area, including 10,697 km of transects over 317 surveys from 7 February 2013 to 10 May 2018 (Figure 1). There were 50 spotted dolphin sightings, and the mean sighting depth was 224.32 m (min = 65.20 m; max = 641.50 m). Group size estimates of spotted dolphins ranged from two to 150 animals, with a mean group size estimate of 42 individuals. Bottlenose dolphins were sighted 75 times during survey effort at a mean depth of 95.51 m (min = 5.90 m; max = 281.70 m). The estimated mean group size of bottlenose dolphins during the survey effort was four animals, and group size estimates ranged from one to 14 individuals.

Dolphin Distribution

Spatial analysis determined that spotted dolphins are widely distributed throughout the Maui Nui region, covering 1,134 km^2 (54%) of the study area (Figure 2a). The predicted density estimates for spotted dolphins ranged from 0.00 to 0.05 sightings/km^2, with the area of highest predicted density in deeper waters (mean depth = 554.46 m), south of Lāna‘i. Bottlenose dolphins in the Maui Nui region were also found to have a wide distribution throughout 1,276 km^2 (60.70%) of the study area, with the predicted density estimate range between 0.00 to 0.04 sightings/km^2 (Figure 2b). In contrast to spotted dolphins, the areas associated with the highest density of bottlenose dolphin sightings were in nearshore, relatively shallow waters (mean depth = 47.63 m).

Vessel Traffic Data Compilation

Vessel data obtained from AIS and tour vessel GPS tracks resulted in 22,464 vessel tracks analyzed for the category of all vessel traffic, and in 12,244 tracks for tour vessels. There were 4,362 tracks from AIS data analyzed for direct commercial transit, recreational, and commercial fishing vessel traffic categories (Table 2). An additional 5,858 AIS tracks had no associated data for vessel type code or were classified as the vessel category “other” and were included in the analysis under the all vessel traffic category. There were brief periods throughout the study timeframe when vessel data were not available from AIS, with a maximum gap of nine consecutive days.

Vessel Traffic Density

Vessel traffic was observed throughout the entire study area, but the density varied widely, with a predicted density range from 0.00 to 2,576.31 tracks/km^2 (Figure 3). Areas of concentrated vessel traffic density corresponded to designated shipping lanes and routes to commonly used locations such as harbors and popular tour trip destinations (Figure 3). Commercial transportation vessel traffic density was highest in shipping lanes and between Lahaina and Manele harbors (predicted density range 0.00 to 448.50 tracks/km^2; Figure 4a). Vessels with unpredictable routes, such as recreational vessels, had the highest density close to shore and were concentrated near the main harbors (predicted density range 0.00 to 15.42 tracks/km^2; Figure 4b). Commercial fishing vessels’ predicted density range was between 0.00 to 23.25 tracks/km^2, concentrated near Lahaina harbor. The vessel traffic of this category appeared to frequent routes in the main channels in the middle of

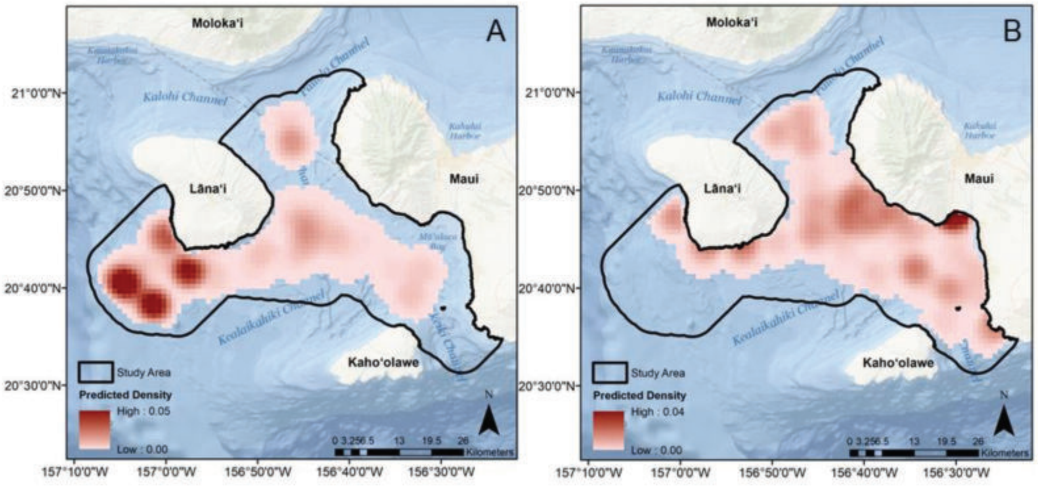

Figure 2. Predicted weighted densities (sightings/km^2) within the study area of (A) pantropical spotted dolphins (*Stenella attenuata*) and (B) bottlenose dolphins (*Tursiops truncatus*) observed during transect surveys from 2013 to 2018 within the Maui Nui region, Hawai‘i.

Table 2. Summary of vessel track data obtained from vessel GPS tracks and AIS vessel data (BOEM & NOAA, 2020) for each vessel type category from January 2014 to December 2017 in Maui Nui, Hawai‘i.

	All vessel traffic*	Commercial transportation vessels	Recreational vessels	Commercial fishing vessels	Tour vessels**
Data availability time period	1 January 2014- 31 December 2017	1 January 2015- 17 December 2017	1 January 2015- 17 December 2017	9 January 2015- 14 November 2017	1 January 2014- 31 December 2017
Percentage of days with vessel traffic (days assessed)	98.2 (1,460)	53.9 (1,095)	12.8 (1,095)	4.9 (1,039)	98.2 (1,460)
Number of vessel tracks	22,464	4,011	256	95	12,244
Distance traveled (km)	675,299.4	168,588.7	4,209.9	1,673.7	350,304.2

*Data sources: AIS download (BOEM & NOAA, 2020), including data with no vessel type code associated and GPS tracks from tour vessels.

**Data sources: Vessel GPS tracks and AIS download (BOEM & NOAA, 2020) from tour vessels; AIS vessel data represent different tour vessels that did not contribute GPS tracks.

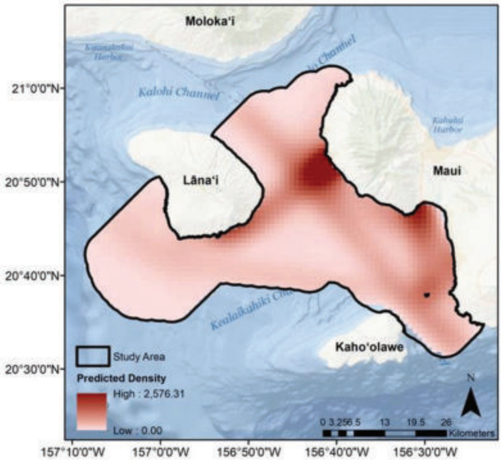

Figure 3. Predicted density of vessel traffic (tracks/km^2) within the study area of all vessel traffic using vessel Global Positioning System (GPS) tracks from tour vessels and Automatic Identification Systems (AIS) vessel data (BOEM & NOAA, 2020) from 2014 to 2017 within the Maui Nui region, Hawai‘i. High and low predicted density values are categorized by the minimum and maximum density estimates for all vessel traffic.

the study area; however, there were also tracks utilizing deeper waters south of Lāna‘i where known fishing buoys exist (Figure 4c). Vessel traffic from tour vessels had the highest density closer to shore (predicted density range 0.00 to 2,126.90 tracks/km^2), with many tracks targeting specific destinations, like popular snorkeling destinations, as depicted in Figure 4d.

Relative Risk Exposure

Within the study area, all vessel traffic presented an exposure risk covering 100% of the area of spotted dolphins' predicted distribution (1,134 km^2; Figure 5). High risk from all vessel traffic to spotted dolphins was concentrated across 82 km^2 of their distribution, specifically, 1 km south of Lāna‘i. Bottlenose dolphins were exposed to vessel risk from all traffic over 100% of their predicted distribution (1,276 km^2), and there was a high risk for 10 km^2 of their entire distribution near Ma‘alaea harbor.

Spotted dolphins were exposed to high commercial transportation vessel traffic risk along a shipping lane on the south side of Lāna‘i, spanning an area of 63 km^2 (Figure 6a). Recreational vessel traffic presented high risk of exposure over 67 km^2 near the south coast of Lāna‘i (Figure 6b). Commercial fishing vessel traffic risk was highest for spotted dolphins over 82 km^2, and was located approximately 10 km off southwest Lāna‘i (Figure 6c). The highest risk from tour vessel traffic to this dolphin species encompassed an area of 101 km^2, concentrated approximately 3 km northeast of Lāna‘i, near the center of the study area between the islands of Maui and Lāna‘i (Figure 6d).

Bottlenose dolphins were exposed to high risk from commercial transportation vessel traffic over an area of 90 km^2 in the shipping lane that traverses the main channel between the four islands and along a route that connects Lahaina and Manele harbors (Figure 7a). The waters outside Ma‘alaea harbor were associated with high risk to bottlenose dolphins from recreational vessel traffic corresponding to 5 km^2 (Figure 7b). Commercial fishing vessel traffic presented high risk over an area

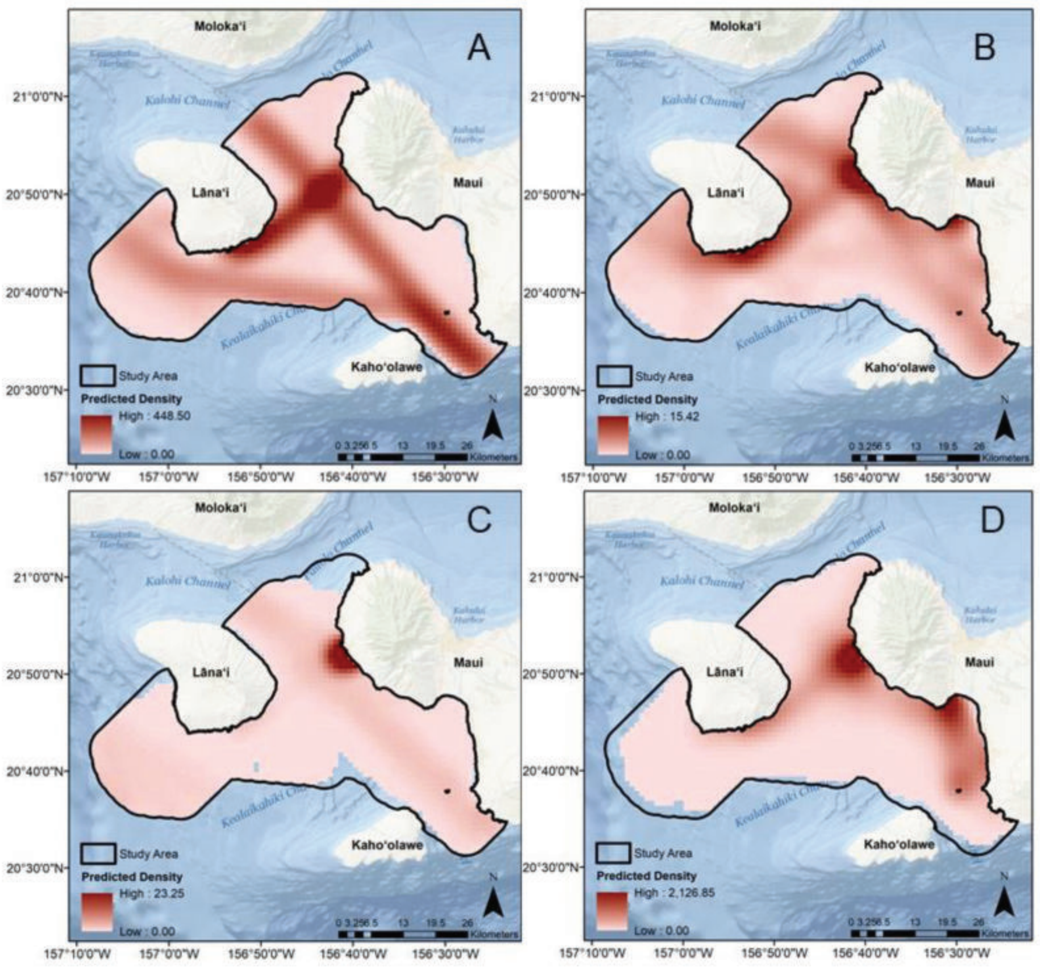

Figure 4. Predicted density of vessel traffic (tracks/km^2) within the study area using vessel GPS tracks from tour vessels and AIS vessel data (BOEM & NOAA, 2020) from 2014 to 2017. High and low predicted density values are categorized by the minimum and maximum density estimates for the vessel categories within the Maui Nui region, Hawai'i: (A) commercial transportation vessels, (B) recreational vessels, (C) commercial fishing vessels, and (D) tour vessels.

of 36 km^2 near Lahaina harbor (Figure 7c). The risk from tour vessel traffic to bottlenose dolphins was highest (risk > 0.9) in a small concentrated area outside of Ma'alaea harbor, covering 10 km^2 (Figure 7d).

Discussion

The increase and diversification of vessel traffic worldwide (Hildebrand, 2009) creates a heightened concern for the conservation of dolphin species due to known impacts (reviewed in Machernis et al., 2018) and the growing number of interactions (Hildebrand, 2009). Within the Maui Nui study area, there is a gap in knowledge regarding the extent of risk that vessel traffic poses to the populations of spotted and bottlenose dolphins. We assessed the risk of exposure to various vessel types for these two island-associated populations by evaluating the overlap of the species' predicted distribution and vessel density. We acknowledge the following caveats to the analysis: (1) differences in the temporal resolution of data used for the vessel and dolphin analysis—data from AIS provided full coverage across a 24-h time period for the majority of the study period, while dolphin research surveys were only conducted during daylight and were limited to a smaller percentage of survey coverage; (2) the presence of vessels was not recorded during the research survey effort,

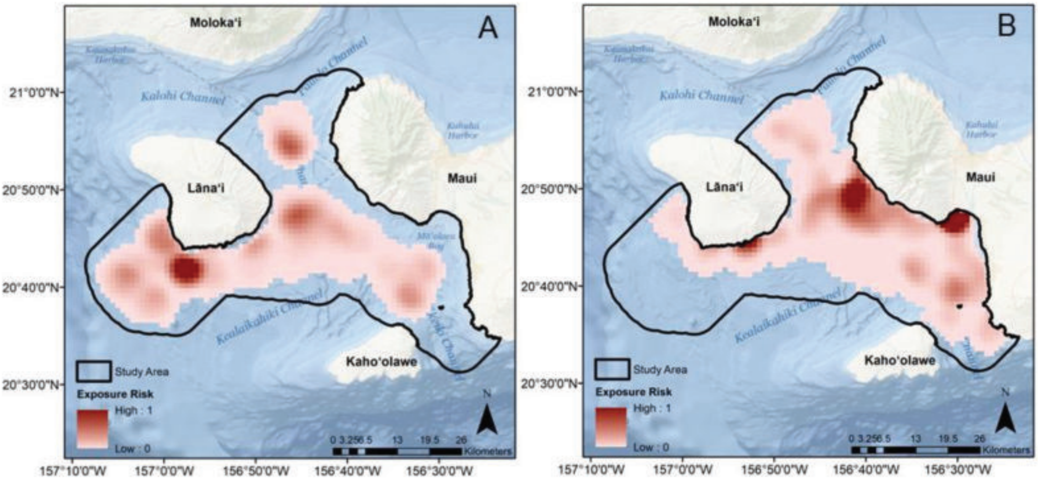

Figure 5. Relative exposure risk from all vessel traffic using vessel GPS tracks from tour vessels and AIS vessel data (BOEM & NOAA, 2020) to (A) spotted dolphins and (B) bottlenose dolphins from 2014 to 2017 within the Maui Nui region, Hawai'i. Risk was measured as the product of dolphin predicted density and vessel traffic predicted density, and is represented on a normalized scale of low (0) to high (1) risk.

and both on- and off-effort dolphin sightings were used for determining dolphin distribution; and (3) temporal or seasonal patterns of vessel traffic or dolphin distribution within the study area were not considered. Despite these limitations, we are confident that the data used accurately represent the overall trends of vessel traffic and dolphin distribution; and, as suggested by Cates et al. (2017), this work provides an important first step in analyzing the risk vessels pose to these species of dolphins in Maui Nui. Furthermore, this is the first article to determine risk to spotted and bottlenose dolphin populations in Hawai'i from different vessel categories. Our results show that there is high risk from vessel traffic to spotted and bottlenose dolphins in the Maui Nui region, exposing both species to risk over 100% of their predicted distribution. Additionally, we determined the risk to these species by vessel category (commercial transportation, recreational, commercial fishing, and tour vessel traffic) varied both spatially and in scale (low to high risk) within the study area.

Within the study area, mapping data from 22,464 vessel tracks that covered a distance of 675,299.40 km over a 3-year period revealed distinct areas of high density vessel traffic. It is worth noting that while commercial vessel traffic was well represented in the AIS dataset, AIS reporting is not required for smaller vessels, which resulted in a smaller sample size for commercial fishing and recreational vessel tracks. Results for these vessel categories should be considered a minimum depiction of actual vessel traffic levels; therefore, the concentration of vessels using the Maui Nui region is of concern for these dolphin populations. For example, previous research determined that dolphins perceive the physical presence of vessels as a risk (Frid & Dill, 2002; Pirotta et al., 2015), which can result in changes in behavioral budgets or displacement from known habitats (Bejder et al., 2006). Vessel noise emissions can cause an acoustic disturbance to dolphins by altering sound characteristics (Guerra et al., 2014) or masking acoustic signals (Pirotta et al., 2015), thereby interfering with communication. Consequently, the repeated and long-term exposure to the physical presence and underwater noise generated from vessel traffic can be a source of chronic stress (Bejder et al., 2006), which can affect the fitness of a population (New et al., 2020). Additionally, vessel strikes can result in lethal or non-lethal injuries to dolphins (Schoeman et al., 2020), and these incidences may present a larger threat to dolphin populations than has been previously discussed (Van Waerebeek et al., 2007). Within the Maui Nui region, there is evidence from long-term photo-identification data of injuries indicative of vessel interactions (e.g., propeller scars, blunt injuries) for three of 397 spotted dolphins and one of 277 bottlenose dolphins (PWF, unpub. data).

This study found risk from vessel traffic throughout 100% of the predicted distribution of each species in the Maui Nui region. Although spatial overlap does not characterize the full extent of risk from vessels to these dolphins, given

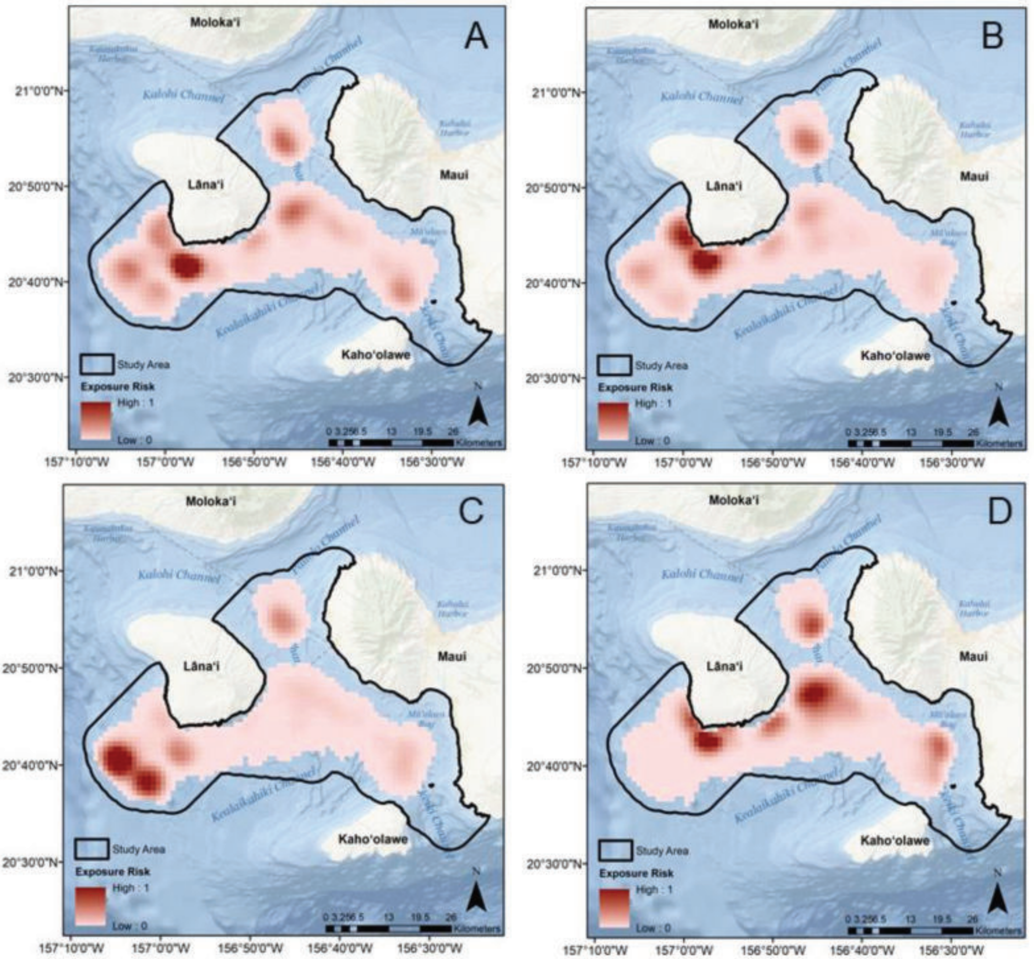

Figure 6. Relative exposure risk to spotted dolphins from vessel traffic using vessel GPS tracks from tour vessels and AIS vessel data (BOEM & NOAA, 2020) from 2014 to 2017 within the Maui Nui region, Hawai'i. Risk was measured as the product of spotted dolphin predicted density and vessel traffic categories predicted density, and is represented on a normalized scale of low (0) to high (1) risk for the following vessel categories: (A) commercial transportation vessels, (B) recreational vessels, (C) commercial fishing vessels, and (D) tour vessels.

these results and the susceptibility of island-associated populations of dolphins to even low levels of anthropogenic disturbance (New et al., 2020), our work suggests that spotted and bottlenose dolphins within the study area may be vulnerable to the threats associated with vessel exposure. Recent work by Self et al. (2021) found overlap between vessel traffic and spinner dolphin and false killer whale (*Pseudorca crassidens*) pods with calves in the Maui Nui region, resulting in elevated risk for the overall fitness of those particular populations. This work aligns with our findings that vessel traffic is likely a conservation concern for spotted and bottlenose dolphin populations in this area. The extent of this threat to the population of spotted dolphins in the Maui Nui region is unknown as there is no current abundance estimate for the 4-Islands stock, which encompasses animals in our study area and additional waters on the windward side of the island (Carretta et al., 2020). A recent publication by Van Cise et al. (2021) found a decrease in the Maui Nui bottlenose dolphin numbers from an estimated 288 animals in 2000 to 64 animals in 2018. While the cause for this reported decline is still unknown, the vulnerability of bottlenose dolphins to vessel traffic in this area is of heightened concern. To gain a greater understanding of the current extent that vessels

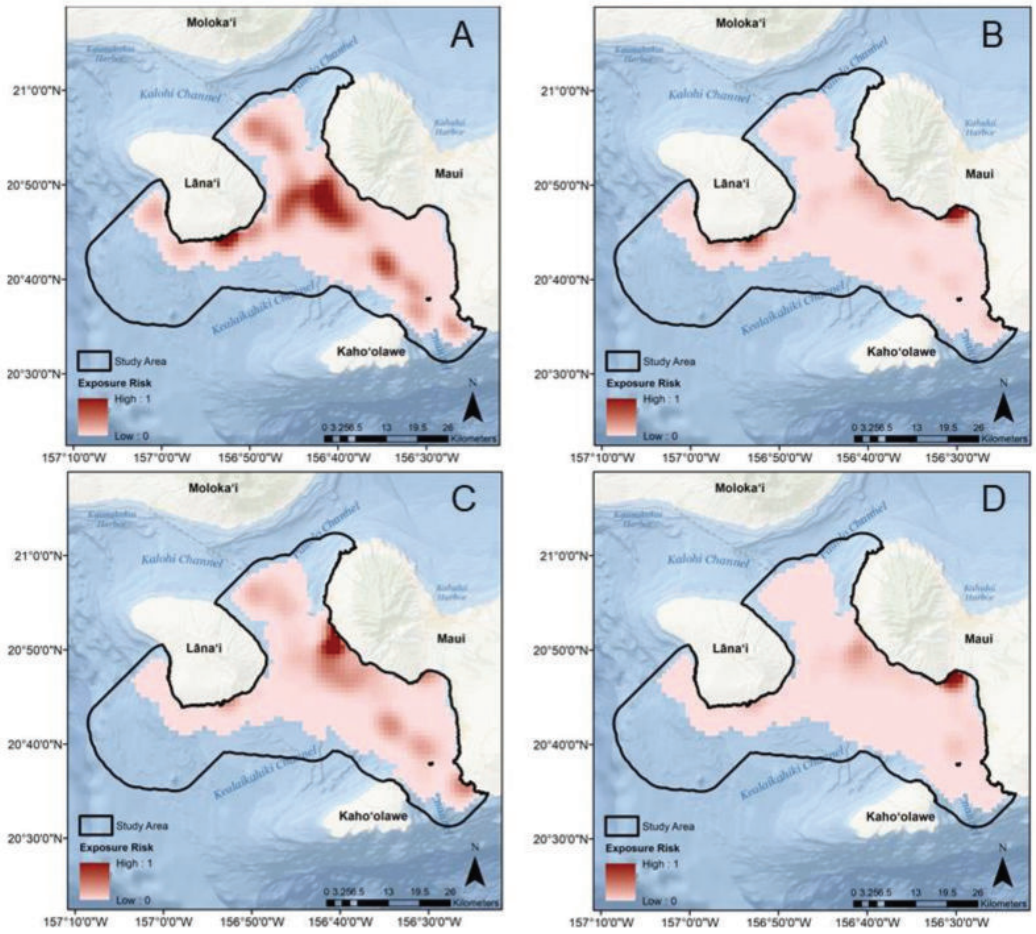

Figure 7. Relative exposure risk to bottlenose dolphins from vessel traffic using vessel GPS tracks from tour vessels and AIS vessel data (BOEM & NOAA, 2020) from 2014 to 2017 within the Maui Nui region, Hawai'i. Risk was measured as the product of bottlenose dolphin predicted density and vessel traffic categories predicted density, and is represented on a normalized scale of low (0) to high (1) risk for the following vessel categories: (A) commercial transportation vessels, (B) recreational vessels, (C) commercial fishing vessels, and (D) tour vessels.

may threaten or disturb these populations, further investigation and consideration of additional factors such as dolphin behaviors (i.e., dive profiles, time at surface) and vessel characteristics (i.e., draft depth, maneuverability, noise emissions) are necessary. This knowledge is of increased importance as the risk from vessels to the dolphin populations presented herein is likely to increase as vessel traffic continues to rise (Hildebrand, 2009).

Our results determined that vessel exposure risk varied by dolphin species and vessel type, illustrating the importance of considering these variations when assessing vessel traffic as a threat to dolphin species. Within the study area, spotted dolphins had the highest risk from all vessel traffic in deeper waters off the south side of Lānaʻi, and tour vessel traffic presented the largest area of high risk over 101 km^2 of their predicted distribution. In Costa Rica, the presence of tour boats was found to elicit behavioral changes in populations of spotted dolphins, including decreases in resting and foraging behavior (Montero-Cordero & Lobo, 2010). Furthermore, evidence of diel behavioral patterns in spotted dolphins in Hawaiʻi (Baird et al., 2001; Baird, 2016) suggests that this population may be at higher risk of vessel disturbance from daytime tourism trips as dolphin groups may be spending more time resting or socializing closer to the surface during the day. Commercial fishing vessel traffic also had a large area (82 km^2) of high risk for spotted dolphins, which is of concern due to the known threats cetaceans face from fisheries interactions in Hawai‘i (Nitta & Henderson, 1993). A study by Baird & Webster (2020) described the risk of fisheries interactions for spotted dolphins in the main Hawaiian Islands where commercial fishing vessels target this specific species to catch the associated fish. The risk from commercial fishing vessel traffic and potential risks from fisheries interactions have clear implications for the population in this study as a recent study found that 13.10% of spotted dolphins in Maui Nui have scarring that is indicative of previous fisheries interactions (Machernis et al., 2021). Additional research is needed to evaluate how temporal variations in dolphin behavior and vessel traffic patterns may impact the extent that vessel traffic, specifically from tour and commercial fishing vessels, threatens spotted dolphins in Maui Nui.

In this study, overall vessel traffic presented the highest risk to bottlenose dolphins in nearshore habitats—those concentrated in the channels and close to harbors. Commercial transportation vessel traffic had the largest area of high risk for bottlenose dolphins. This likely demonstrates an increased threat for this dolphin population as vessels on predictable routes, such as high-speed ferries (Baş et al., 2015) and large shipping vessels (Mattson et al., 2005), have previously been found to incite negative behavioral disturbance responses in other populations of bottlenose dolphins. Furthermore, the vessel noise emissions from commercial vessels have been found to reduce the communication space for marine mammals up to 99% (Putland et al., 2017), which could interfere with hearing and acoustic communication among bottlenose dolphins (Erbe et al., 2019). We also found a highly concentrated area of high risk from tour vessels to bottlenose dolphins (risk > 0.9) near Ma‘alaea harbor, indicating an elevated chance of vessel–dolphin co-occurrence resulting in potential dolphin disturbance or collision. The popularity of wildlife viewing tours in Hawai‘i (Wiener et al., 2020) places bottlenose dolphins at an increased risk of targeted interactions in the nearshore environment where tour vessel traffic is concentrated. These shallow water coastal environments are susceptible to increased sound pollution in the soundscape, especially from small vessels (Wilson et al., 2022), which can mask communication and incite behavioral responses from dolphin species (Erbe et al., 2019). Other disturbance responses to tour vessels have been extensively studied in other populations of bottlenose dolphins and range from avoidance behavior in Shark Bay, Western Australia (Bejder et al., 2006), to decreased foraging in Moray Firth, Scotland (Pirotta et al., 2015), and decreased resting behaviors in Doubtful Sound, New Zealand (Lusseau, 2003b). Within the Maui Nui region, individual bottlenose dolphins in the island-associated population demonstrate strong site fidelity within a small home range (Van Cise et al., 2021). As such, the population may be at an increased risk of disturbance and more susceptible to vessel impacts (New et al., 2020). Therefore, we recommend that researchers evaluate how varying levels of vessel traffic exposure affect bottlenose dolphins in Maui on an individual and population level, with a focus on tour and commercial vessel traffic.

Our results provide a baseline knowledge regarding the risk vessel traffic may pose to the island-associated populations of spotted and bottlenose dolphins based on their spatial distribution in the Maui Nui region. This work also highlights differences in vessel risk by dolphin species and vessel category using methods that can be applied to evaluate vessel exposure in other dolphin populations. Based on our results, additional information is needed to assess the implications of the high vessel risk to the spotted and bottlenose dolphin populations in Maui Nui, including the impact of temporal patterns in dolphin distribution and vessel traffic density. We encourage future researchers to evaluate dolphin behavior as it relates to exposure from different vessel types based on factors such as vessel speed, approach type, maneuverability, and noise characteristics on both an individual and population level. This study is an important first step in understanding the potential threat of vessel traffic to these highly vulnerable dolphin populations and should be used as a guide for future research that aims to effectively aid in their conservation.

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