A NOVEL APPROACH TO ESTIMATE THE DISTRIBUTION, DENSITY AND AT-SEA RISKS OF A CENTRALLY-PLACED MOBILE MARINE VERTEBRATE

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A Novel Approach to Estimate the Distribution, Density and At-Sea Risks of a Centrally-Placed Mobile Marine Vertebrate

ABSTRACT

Formulating management strategies for mobile marine species is challenging, as knowledge is required of distribution, density, and overlap with putative threats. As a step towards assimilating knowledge, ecological niche models may identify likely suitable habitats for species, but lack the ability to enumerate species densities. Traditionally, this has been catered for by sightings-based distance sampling methods that may have practical and logistical limitations. Here we describe a novel method to estimate at-sea distribution and densities of a marine vertebrate, using historic aerial surveys of Gabonese leatherback turtle (*Dermochelys coriacea*) nesting beaches and satellite telemetry data of females at sea. We contextualise modelled patterns of distribution with putative threat layers of boat traffic, including fishing vessels and large ship movements, using Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data. We identify key at-sea areas in which protection for inter-nesting leatherback turtles could be considered within the coastal zone of Gabonese Exclusive Economic Zone (EEZ). Our approach offers a holistic technique that merges multiple datasets and methodologies to build a deeper and insightful knowledge base with which to manage known activities at sea. As such, the methodologies presented in this study could be applied to other species of sea turtles for cumulative assessments; and with adaptation, may have utility in defining critical habitats for other central-place foragers such as pinnipeds, or sea bird species. Although our analysis focuses on a single species, we suggest that putative threats identified within this study (fisheries, seismic activity, general shipping) likely apply to other mobile marine vertebrates of conservation concern within Gabonese and central African coastal waters, such as olive ridley sea turtles (*Lepidochelys olivacea*), humpback dolphins (*Sousa teuszii*) and humpback whales (*Megaptera novaeangliae*).

Keywords: inter-nesting, leatherback turtles, marine protected area (MPA), spatial analysis, Automatic Identification System (AIS), Vessel Monitoring System (VMS)

1. INTRODUCTION

Multiple modelling techniques exist to build an understanding of habitat niches for species in the marine environment (Aarts et al., 2008; Edrén et al., 2010; Forney et al., 2015; Matthiopoulos et al., 2004; Pikesley et al., 2014; Wedding et al., 2016). These methods are challenged by the issue of enumerating species densities, which has traditionally relied upon sightings-based distance sampling (Buckland et al., 2001), with data being collected primarily by way of boat or aerial surveys (Aerts et al., 2013; Becker et al., 2014; Hammond et al., 2002). Typically, distance sampling relies on three key assumptions being met (Thomas et al., 2010); species are detected with certainty, species do not move, distance measurements are exact (Thomas et al., 2010). As such, application of distance sampling methodologies to aerial based surveys have helped reveal density patterns across a broad spectrum of marine species 'at sea' (Lauriano et al., 2011; Scheidat et al., 2012; Seminoff et al., 2014) and have also proved their efficacy in enumerating densities of marine species whilst on land (Stapleton et al., 2015).

However, many marine species are challenging to observe at sea because of their cryptic nature, spending limited time at the sea surface, or due to restrictions imposed by environmental conditions (weather and sea state) (Evans & Hammond 2004). To provide for an alternative complementary process to estimate at-sea distributions and relative densities, we formulated a method that was independent of the need to visually sight species at sea, that instead utilised existing available data: aerial surveys of leatherback turtle nest counts and satellite tracking data.

Increased understanding of spatial and temporal habitat use, together with associated densities, may facilitate successful management strategies. However, design, implementation and regulation of protection for mobile marine species is challenging; particularly for far ranging, pelagic and migratory species (Briscoe et al., 2016; Hyrenbach et al., 2000). Defining appropriate spatial and temporal bounds to managed areas is more tractable when animals seasonally aggregate (Maxwell et al., 2014; Whittock et al., 2014; Witt et al., 2008). In 2002, the central African country of Gabon created a system of coastal and terrestrial National Parks with the aim of protecting key areas of biodiversity-rich habitats. Thirteen National Parks were designated, including a single marine park to the south of the country at Mayumba (Fig. 1). Gabon's beaches support important nesting sites for sea turtles, including globally important breeding aggregations for the leatherback turtle (*Dermochelys coriacea*); the Southeast Atlantic Ocean subpopulation is currently listed as IUCN Red List Data Deficient (Tiwari et al., 2013). The northern and southern extremes of the Gabon coast (Pongara and Mayumba National Park) receive the highest densities of nesting activity (Witt et al., 2009). Additionally, the olive ridley (*Lepidochelys olivacea*), green (*Chelonia mydas*) and hawksbill sea turtles (*Eretmochelys imbricata*) also nest (Casale et al., 2017; Maxwell et al., 2011; Metcalfe et al., 2015).

The leatherback turtle is highly migratory with expansive post-nesting dispersal patterns (Fossette et al., 2014; Roe et al., 2014), but will seasonally aggregate off Gabon’s nesting beaches. Protection of large scale aggregations likely represents a significant management target within coastal waters (Hitipeuw et al., 2007; Nel et al., 2013; Roe et al., 2014; Witt et al., 2008). However, for protection to be effective, density and distributions of turtles need to be ascertained and relevant threats identified, and if possible quantified, preferably in space and time. In the marine environment, sea turtles may negatively interact with a broad suite of vessel activity. These interactions can lead to bycatch from coastal (Alfaro-Shigueto et al., 2007; Lum, 2006; Witt et al., 2011) and oceanic (Huang, 2015; Lewison et al., 2004) fisheries, boat strike (Denkinger et al., 2013; Nabavi et al., 2012), crude oil contamination (Follett et al., 2014), or possible displacement from critical habitats or auditory damage from seismic surveying (Nelms et al., 2016). Within Gabon’s territorial waters bycatch from fisheries (Casale et al., 2017) and/or boat strike (Billes et al., 2003) may negatively impact leatherback turtles. There is also extensive offshore petrochemical extraction primarily located to the south of Port Gentil (http://www.seaturtle.org/mtrg/projects/gabon/MarineAtlas.pdf).

At-sea vessel activity may be gathered by both Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data. The use of VMS, primarily as a tool for providing at-sea densities of fisheries (Hintzen et al., 2012; Vermard et al., 2010; Witt and Godley, 2007) has revolutionised the process of mapping, analysing and interpreting fisheries activity patterns.

The advent of AIS may prove to provide additional capabilities due to time resolution of data (Natale et al., 2015) and inclusion of multiple vessel types (Shelmerdine, 2015). The installation and operation of VMS is discretional among maritime nations; the requirement to fit AIS systems is, however, mandatory aboard vessels making international voyages with gross tonnage ≥ 300 t, cargo vessels ≥ 500 t and all passenger ships regardless of size (Shelmerdine, 2015).

In this study, we combine aerial survey nest count data for leatherback turtles together with satellite telemetry data from nesting females and contextualise these with VMS and AIS data. Our aims were to: (i) model leatherback turtle distribution and relative density at sea using a method that was independent of the need to sight species at sea, (ii) investigate areas of spatial overlap between leatherback turtles and putative threats from vessels associated with multiple industry categories, and (iii) identify key areas for inter-nesting leatherbacks within the Gabonese Exclusive Economic Zone (EEZ) that may benefit from application of Marine Protected Areas (MPAs).

2. METHODS

2.1. Aerial survey data

Aerial surveys were flown along the Gabonese coast using a variety of high-wing light aircraft (Supplementary Material, Table A.1) as described in (Pikesley et al., 2013). Surveys were organised to coincide with the main period of leatherback turtle nesting activity (December-February; (Witt et al., 2009)). Multiple surveys were conducted in 2002/03 (*n* = 2), 2005/06 (*n* = 3) and 2006/07 (*n* = 3), with no surveys in 2003/04 and 2004/05. Each survey represented a 600 km flight path (approximate straight-line distance). Flights commenced at dawn. Surveys were timed to coincide with periods when the maximum width of the nesting beach was unaffected by tide during early morning daylight hours, hence ensuring the greatest number of nesting activities could be recorded after sunrise and before the next high tide removed traces of activity. Surveys were typically split over two days to take advantage of morning low sun angle, which aids detection of marine turtle nesting tracks during video analysis.

Survey aircraft were flown at a groundspeed of 180 to 190 km hr^{-1} at an altitude of 50 to 60 m, with the aircraft positioned 100 to 200 m offshore. Surveys were flown in a southeast direction from north to south, parallel to the coastline. The survey start location was northern most limit of Pongara National Park (Fig. 1). The survey end location was the southern limit of Mayumba National Park's border with the Republic of Congo. A 50 km section of coast to the north and east of Port Gentil was excluded from all surveys as this area consisted of mangroves and mudflats, which are unlikely to support leatherback turtle nesting activity.

A video camera was used to record footage of the nesting beach during each aerial survey. Leatherback turtle nesting activities were then counted from this video data in accordance with the methodology described by (Witt et al., 2009). These counts were aggregated into approximate 500 m linear sectors of beach (data bins) that were defined by waypoint data collected continuously by hand-held Global Positioning System (GPS) receivers aboard the aircraft at the time of the aerial surveys. A longitude/latitude (World Geodetic System (WGS) 1984 format) midpoint was determined for each of these data bins to which the counts were then associated.

2.2. Satellite tracking data

Platform Transmitter Terminals (PTTs) were attached to thirty-seven adult female leatherback turtles at nesting locations in Gabon throughout the nesting season (October to February: 2005/06 (*n* = 8), 2006/07 (*n* = 2), 2007/08 (*n* = 5), 2008/09 (*n* = 10), 2009/10 (*n* = 2) and 2012/13 (*n* = 10)). Turtles were tagged within the National Parks of Pongara (*n* = 18) and Mayumba (*n* = 19); inter-nesting movements of 7 of these turtles were previously published in (Witt et al., 2008) (Fig. 1, and see metadata in Supplementary Material, Table A.2.). Methods of turtle capture, transmitter type and process of attachment are detailed in Witt et al. (2011).

Satellite telemetry data were collected using the Argos satellite system (CLS, 2011) and downloaded with the Satellite Tracking and Analysis Tool (STAT) (Coyne and Godley, 2005). All locations with accuracy class Z and 0 were removed (Witt et al., 2010). Data were imported into the Geographical Information System (GIS) ArcMap 10.1 (ESRI, Redlands, USA http://www.esri.com) and visually assessed to determine nesting events for each female. Nesting events typically occurred every 9 to 11 days, the night-time location with the highest accuracy location class and located on, or nearest to land within this time-frame was chosen as indicative nesting event. Satellite tracking location data were then apportioned by these inter-nesting periods. Five turtles departed the Gabon coast immediately after attachment of the PTT; these data were not used in further analysis.

2.3. Modelling leatherback turtle distribution and relative density at sea

2.3.1. Estimating leatherback turtle inter-nesting footprint at sea

For each set of inter-nesting data (turtles *n* = 32, inter-nesting datasets *n* = 121: 2005/06 (*n* = 4), 2006/07 (*n* = 3), 2007/08 (*n* = 6), 2008/09 (*n* = 35), 2009/10 (*n* = 12) and 2012/13 (*n* = 61)) we applied a speed and azimuth filter (Freitas et al., 2008; Witt et al., 2010); filtering was undertaken in R (R Development Core Team 2008; R package: argosfilter (Freitas, 2010)). Working in a projected coordinate system (Africa Albers Equal Area Conic (AAEAC)) the geometric centroid of these data was determined together with the distance of each location from the centroid; to remove spatial outliers we peeled data to the 95th quantile. The ellipsoid hull of these data was then calculated (R Development Core Team 2008; R package: cluster (Maechler et al., 2015)), this being the minimum area such that all given points lay inside, or on the boundary of the ellipsoid. An ellipsoid hull was chosen as this represents a regular geometric form which can be constructed from component metrics (i.e. semi major/minor axis, centroid and azimuth). In the presented analysis, the number of inter-nesting locations used to fit ellipsoids necessarily varied (median *n* = 71 locations, inter-quartile range *n* = 52 to *n* = 94, range: min n = 10, max n = 218). The length (km) of the semi-major and semi-minor axes, the area (km^2) of the bounding ellipse, together with the shortest distance (km) (great-circle-distance: Haversine formula) of the centroid to the coast were determined. All metrics were expressed as a single value per turtle, averaging (mean) where necessary for multiple inter-nesting periods. There was no significant difference in the median semi-major, semi-minor, or offshore distance for leatherback turtles between the nesting locations of Pongara and Mayumba National Parks (Supplementary Material, Table A.3.). We therefore calculated single countrywide median values for each ellipse metric irrespective of release location.

2.3.2. Linking inter-nesting footprint to aerial survey data

The average (mean) number of leatherback turtles km^{-2} (at sea) per nesting season was calculated using the following approach. We produced a smoothed coastline vector using a 40 km smoothing window. For each aerial survey dataset we used a spatial join in ArcMap to assign ellipse metrics and coastal orientation to the midpoint coordinates of the data bins (data were joined to the nearest existing location). These coordinates (projected coordinate system: AAEAC) were then transposed offshore, perpendicular to the coast, using distance of centroid to the coast (offshore distance) and coastal bearing.

For each offshore coordinate pair, with its associated aerial survey data bin, we projected an ellipsoid polygon (major axis parallel to the coast), using grand averaged semi-major/minor axes and azimuth (coastal bearing). Each individual polygon surface was coerced to a raster of 1 x 1 km resolution and each raster cell assigned a turtle density at sea (km^{-2}) which was calculated from the aerial survey data as follows. To provide for an annual estimate of the total number of nesting activities attributable to the data bin we divided the number of tracks recorded on the day of the aerial survey by the proportion of nesting activities expected for the day of the aerial survey. This proportion was determined from a normally distributed seasonal nesting curve with approximations for the beginning and end of the nesting season of 1st October to 30th April respectively (see Witt et al., (2009) for detailed analysis of leatherback turtle nesting effort in Gabon). This newly calculated annual nesting effort was then divided by a clutch frequency of 6.17 (± 0.47 SD (Miller 1997)), to provide the total number of turtles nesting within the data bin for the season. Finally, we divided this total by the sea area of the propagated ellipse to provide an at-sea density of leatherbacks turtles (turtles km^{-2}) which was then assigned to each raster cell. Resulting rasterised polygons were then stacked and summed to provide a composite raster surface (for each aerial survey) that described an estimate of the at-sea density (km^{-2}) of inter-nesting leatherback turtles for the nesting season.

These raster surfaces were then apportioned into two that reflected: (i) the peak months of the Gabonese leatherback nesting season (December, January, February) and, (ii) the pre- and post-peak months (October, November, and March, April) using a ratio derived from the seasonal nesting curve. Where multiple aerial surveys had been flown within a nesting season these surfaces were then averaged (mean); a grand average (mean) raster was then calculated across all nesting seasons.

2.4. VMS data: density mapping

We sourced Vessel Monitoring System (VMS) data from the Government of Gabon, for Gabon flagged trawl vessel fishing activity within the Exclusive Economic Zone (EEZ) of Gabon for 2010, 2011 and 2012. Fisheries primarily target prawns and shrimp, sardines, tuna and a range of demersal fish species (Casale et al., 2017). The VMS data represented the best possible continuous dataset available and contained 1 053 923 recorded locations (2010 (n = 209 033), 2011 (n = 452 531), 2012 (n = 392 359)). All vessel identifications numbers were anonymised, as such, each VMS record consisted of a pseudo-vessel reference number, date/time stamp (UTC), geographic coordinates in decimal degrees (WGS 1984) and vessel type (by fishing gear). Data were apportioned annually; 1st October to 30th September to reflect the seasonality of leatherback turtle nesting: 2010/11 (n = 429 554), 2011/12 (n = 420 807).

For each annual VMS dataset, data were ordered by vessel reference number and date/time stamp. Distance and time elapsed were calculated between each location, and vessel speed calculated in knots. A speed rule was used to distinguish fishing from steaming or near-stationery movement (Witt and Godley, 2007); only data with speeds ≥ 1 or ≤ 5 knots were retained. Data were then apportioned into three seasonal groups: (i) October and November (pre-peak leatherback nesting season), (ii) December to February (peak) and (iii) March and April (post-peak). Seasonally grouped data were then processed as follow. For each vessel, location data were then summarised (counts) to a 10 x 10 km resolution raster with only the first location per day per cell being counted. This raster resolution was iteratively determined to provide an optimum cell size that facilitated meaningful map interpretation. This process was repeated for both annual datasets and the resulting rasters averaged (mean). These seasonal vessel-density rasters were then divided by the respective numbers of days of the season (*i.e.* October - November: n = 61 d) to provide a surface that described the average (mean) number of unique vessels day^{-1} within each 10 x 10 km raster pixel.

2.5. AIS data: density mapping

We sourced ground and space merged Automatic Identification System (AIS) data from ExactEarth (http://www.exactearth.com) for 2012, 2013 and 2014 for the EEZ of Gabon (space-borne AIS data are not available prior to 2012). This dataset contained 22 791 353 recorded locations (2012 (*n* = 3 719 235), 2013 (*n* = 7 043 142), 2014 (*n* = 12 028 976)). Each record consisted of Maritime Mobile Service Identity (MMSI) number, date/time stamp (UTC), geographic coordinates in decimal degrees (WGS 1984) and speed (knots). Records with speed = 0 knots were removed. Vessels were assigned into one of five categories: cargo *n* = 2240 (39%), oil (support vessels: including tankers carrying crude/refined oil and other petrochemical related products) *n* = 1535 (27%), oil (seismic research) *n* = 45(1%), fishing *n* = 106 (2%) and miscellaneous (*e.g.* tug, passenger, recreational: *n* = 1150 (20%)); 685 (12%) vessels could not be assigned to a category due to insufficient metadata. Data were apportioned annually, 1st October to 30th September to reflect the seasonality of leatherback turtle nesting: 2012/13 (*n* =

4 637 128), 2013/14 (*n* = 6 327 527) and then divided into three seasonal groups (i) October and November (ii) December to February and (iii) March and April.

For each seasonal dataset location data for the categories, cargo, oil (support vessels), oil (seismic research) and fishing were treated as follows. A speed rule was used to remove locations where vessels were not 'under-way' or exhibited near-stationery movement; only data with speeds ≥ 1 knot were retained. For each category, location data for each vessel were summarised (counts) to a 10 x 10 km resolution raster with only the first location per day per cell being counted. This process was repeated for both annual datasets. Resultant rasters were averaged and seasonal vessel-density rasters calculated that described the average (mean) number of unique vessels day^{-1} within each 10 x 10 km raster pixel.

2.6. Calculating spatial overlap between leatherback turtles and vessel distribution

Spatial overlap between vessel distribution and inter-nesting leatherback turtles was calculated as follows. Seasonal vessel density rasters (trawl and longline/purse seine fisheries, oil support, research and cargo vessels) were re-scaled to 0-1, summed and clipped to the extent of the leatherback turtle density raster. These were then multiplied with our seasonally apportioned leatherback density rasters to provide seasonal unitless relative threat indices for: (i) the complete nesting season, (ii) the peak months (December, January, February) and (iii) the pre- and post-peak months (October, November, and March, April). To provide for data at the same spatial resolution we re-sampled our leatherback turtle at-sea density raster to the same resolution (10 x 10 km) as our VMS and AIS layers using bilinear interpolation.

3. RESULTS

3.1. Leatherback turtle satellite tracking and spatial density patterns

Thirty-two leatherback turtles (Pongara $n = 18$, Mayumba $n = 14$) were tracked for 121 inter-nesting periods (Pongara $n = 101$, Mayumba $n = 20$) with an average time between nest events of 10 ± 1days (mean ± 1 SD; range 7 - 13 days). Turtles primarily remained within continental shelf waters (depths ≤ 200 m), with 93.8% (Pongara; $n = 9530$) and 93.1% (Mayumba; $n = 1504$) of all recorded locations in these waters. Off the coast of Gabon, the continental shelf break lies approximately 45 km from the coast to the north of the country (north of Port Gentil), 50 to 60 km to the south of the country and within 6 km of the coast at Port Gentil. Nintey-one percent ($n = 10749$) of all locations were located within the Exclusive Economic Zone (EEZ) of Gabon (Fig. 1).

The modelled spatial pattern of inter-nesting leatherback turtles at sea indicated that the coastal waters of Pongara and Mayumba National Parks had high densities of inter-nesting leatherbacks, with a smaller hotspot offshore from Sette Cama Reserve and to the south of Port Gentil; greatest density was within and neighbouring the Mayumba Marine Park (Fig. 1).

3.2. VMS and AIS density mapping

3.2.1 Fisheries

Mapping of VMS data for Gabon trawl vessels (October to April) indicated presence of vessels across the majority of coastal waters, with peaks in density to the south of Pongara National Park, and in near-shore waters of Loango National Park. There was negligible activity off the continental shelf (Fig. 2a). Analysis of AIS fishing vessel data for longline and purse seine fisheries, in general, indicated higher density of vessels in offshore waters, approximately 100 - 200 km southwest of Loango National Park (Fig. 2e). There was relatively little activity on the continental shelf, with the exception of a small high-density area to the south of Mayumba National Park. These distinctions in spatial patterns largely reflect the difference in gear type used by these fisheries. There was no duplication of vessels among AIS and VMS datasets.

Apportioning AIS and VMS fisheries data by leatherback nesting season revealed seasonal patterns for both these datasets. Mapping of VMS data indicated a north/south shift in fishing activity. Maximum densities occurred in October/November near Pongara and Loango National Park. Densities remained high at Loango within the months of December to April, but decreased at Pongara (Fig. 2b,c,d). Mapping of AIS data indicated that October/November were peak months for longline and purse seine fisheries with maximum densities occurring southwest of Loango National Park. There was an indication of increased fisheries activity immediately to the south of Mayumba Marine Park during October to February (Fig. 2f,g,h).

3.2.2. Oil industry and cargo vessels

Mapping of AIS data (October to April) revealed marked differences between vessel categories. For example, oil support vessels formed defined routes between the ports of Libreville and Port Gentil, as well as westward from Port Gentil (Fig. 3a). Mapping the distribution of cargo vessels (*i.e.* bulk carriers, container vessels) identified two routes. The first lay parallel to the coast from Port Gentil in the north to the Gabon/Congo EEZ border in the south and broadly mirrored the 200 m isobath, the second ran westward from the port of Libreville (Fig. 3i). There was no marked differences among seasonal density mapping for oil support vessels, or for cargo vessels (Fig. 3b,c,d,j,k,l). Hotspots of seismic vessel movement occurred in continental shelf waters, and were primarily concentrated to the south of Port Gentil and in coastal waters of Loango National Park and Sette Cama Reserve (Fig. 3e). There were clear differences among seasonal density mapping for seismic vessels. There was relatively high seismic vessel presence to the southwest of Mayumba Marine Park at the beginning of the nesting season (October/November), to the south of Port Gentil during peak season (December to February) and in coastal waters of Loango National Park in March/April (Fig. 3f,g,h). These seasonal differences may reflect seasonal legislative restrictions or indicate interest in exploitation. However, it should be noted that presence of seismic vessels does not necessarily indicate vessels were engaged in seismic survey activity.

3.3. Spatial overlap between leatherback turtles and vessel distribution

Mapping spatial overlap of leatherback turtles and vessel distribution indicated that the coastal waters of Pongara and Mayumba National Park were subject to high levels of putative threat throughout the leatherback nesting season (Fig. 4b). There were also isolated areas of moderate/high putative threat within coastal waters from Port Gentil to Sette Cama Reserve, primarily due to coastal fisheries and seismic vessels present within the area. There was variation in magnitude and timing of threat among locations. Spatially, co-occurrence was greatest at Pongara at the beginning of the season (October/November) (Fig. 4d), principally due to the heightened level of coastal fisheries activity, and from Port Gentil to Sette Cama and within and adjacent to Mayumba Marine Park during peak season (December/January/February) and post-peak (March/April) (Fig. 4f,h).

4. DISCUSSION

Sightings-based distance sampling (Buckland et al., 2001) is likely the most widely used method to determine densities of animals at sea, relying on data being collected either by way of boat or aerial transect (Aerts et al., 2013; Hammond et al., 2002). Whilst distance-sampling is well established and relatively accessible it has some limitations (Evans and Hammond, 2004). The presented analysis sought to develop a complementary methodology to estimate at-sea distributions and relative densities that was independent of the need to sight species at sea, and that in turn could be applied to other species of sea turtles for cumulative assessments. With adaptation, this methodology may also have utility in defining critical habitats for other central-place foragers such as pinnipeds, or sea bird species (Cronin et al., 2013; Grecian et al., 2010; Sharples et al., 2012).

Ecosystem based impact assessments can identify areas where cumulative threat may be at its greatest within the marine environment (Halpern et al., 2008), but may not take into account distribution and densities of species within these areas. Furthermore, it is possible that areas subject to relatively high cumulative threat, and with high species densities, will fail to attract adequate conservation effort (Lewison et al., 2014). Identifying key areas where species aggregate may facilitate the decision process of where and when to best place conservation resources to achieve maximum benefit (Hart et al., 2012). With this analysis, we sought to further the process of impact assessment by formulating a cumulative threat index that assessed multiple threats from vessels, whilst at the same time integrating modelled distribution and densities of a species of conservation concern. Our analysis does not attempt to differentiate threats from vessels by magnitude, or relative importance. Whilst the presented analysis is primarily spatial in nature, we also sought to present these spatial patterns in relation to the peak and pre- and post-peak months of the leatherback nesting season. However, threat to turtles and subsequent impacts will also be related to other compounding factors such as turtle behaviour (diving or at surface) and temporal influences such as seasonal fisheries activity (deployment of season-specific gear types) or oil industry activity/spills. It remains likely that many 'threats' require further knowledge or assessment to quantify probable impacts. To do so effectively, species sensitivity to threats needs to be assessed, this in turn, would additionally allow assignment of weights for calculating cumulative impact.

Our analysis revealed that within the peak leatherback nesting season (December to February), when approximately 80% of the season's nesting takes place (Witt et al., 2009), greatest densities of leatherback turtles likely occur in coastal waters adjacent to Pongara and Mayumba National Parks, with a smaller 'hotspot' to the west of Sette Cama Reserve. Contextualising these at-sea density and distribution patterns, with vessel movements derived from VMS and AIS location data, suggests that vessels associated with various industries have the potential to interact with inter-nesting leatherback turtles within Gabonese coastal waters, throughout the nesting season.

Density mapping of the Gabon trawl fisheries fleet (for which VMS data were available) indicated that this fleet could interact with at-sea leatherbacks at all high-density leatherback areas. In coastal waters adjacent to Pongara National Park, the potential for this was greatest at the start of the nesting season. There was a subsequent southerly shift in vessel densities for coastal fisheries later in the nesting leatherback season. Analysis of AIS fisheries data, which predominantly comprised of large Distant Water Fleet (DWF) vessels, suggested that there was no activity for this category of vessel within coastal waters of Pongara National Park. There was however, a hotspot of DWF vessel activity just within, and adjoining the southwest/south-easterly border of Mayumba Marine Park at the start of, and during peak nesting season. The coastal waters of Pongara National Park had the highest density of vessels associated with shipping routes for both oil industry and cargo vessels. There were notable hotspots of vessel movements both between the ports of Libreville and Port Gentil in coastal waters, and offshore from these ports to the open ocean, throughout the nesting season. Seismic vessel activity was primarily confined to the coastal waters south of Port Gentil and to the southwest of Mayumba Marine Park. The coastal waters of Pongara National Park had high levels of cumulative threat throughout the nesting season. Cumulative threat mapping indicated the coastal waters from south of Port Gentil to Mayumba National Park had greatest levels of cumulative threat through the peak and post-peak nesting season.

Several caveats must be considered when interpreting the findings of this study. Our approach only uses data sourced from adult females and therefore does not consider juvenile or male turtle habitat use. The distribution and density estimates of female leatherback nesting activity were derived from aerial survey data sourced from seven aerial surveys (2002/03 to 2006/07). Inclusion of additional aerial survey data within this analysis may modify model outputs; although unpublished data (Formia pers. comm.) suggests nesting patterns are similar. Our method does not account for any temporal variability in nesting season that may be present between the north and south of the country (Witt et al., 2009). This would be unlikely to affect the modelled at-sea densities of leatherbacks, but should be considered when interpreting threat mapping. Similarly, our method utilises a normally distributed nesting curve to calculate annual estimates of the total number of nesting activities for each data bin, with approximations for the beginning and end of the nesting season of 1st October to 30th April respectively. These estimates would be slightly modified under alternative curve scenarios. To calculate the total number of turtles nesting within each data bin for the season we applied a clutch frequency of 6.17 (Miller 1997). As our main goal was to demonstrate overlap of turtle distribution and density with vessel activity using a relative threat index the value for clutch frequency was not critical. However, it should be noted that clutch frequency is a critical metric in determining population abundance (Esteban et al., 2017).

It is also probable that our vessel densities represent underestimations. Our analysis only considers vessels that are legally required to transmit their locations by way of VMS or AIS. Similarly, these systems need to be enabled and transmitting. Applying a slow speed filter to all AIS data to remove vessel traffic that was not 'under-way' may have the effect of removing some locations for vessels deploying purse seine gear; although, it is highly unlikely that a vessel will remain motionless 'at sea' given the influence of wind and or tide and currents. For coastal fisheries, we only evaluate data for the Gabon fleet. Vessel movements for DWFs and artisanal fisheries are not considered; therefore, these sectors remain un-assessed. In addition, our VMS data are sourced prior to September 2012. Subsequent changes to fisheries management regimes within Gabon, including the definition of no-take and exclusion zones, are likely to have modified vessel movement patterns in the vicinity of these zones. Finally, whilst some of our component data layers do not overlap temporally, primarily due to logistical or financial constraints, they represent the best available data from which to formulate this analysis. Notwithstanding these temporal inconsistencies, we consider that the methodology presented is sound and capable of generating realistic density estimates. However, we acknowledge that these density estimates and associated threat indices may be improved with temporally concurrent data.

Although the presented analysis focuses on a single species, much of the associated threats will apply to other air-breathing mobile marine vertebrates in Gabonese coastal waters. These species include olive ridley sea turtles (Maxwell et al., 2011; Metcalfe et al., 2015), humpback dolphins (*Sousa teuszii*) (Collins, 2015; Weir and Collins, 2015) and humpback whales (*Megaptera novaeangliae*) (Rosenbaum et al., 2014); although mitigation and management measures would undoubtedly be species specific. Such an approach to monitoring key activities of relevance to conservation is considered among the key global priorities for cetacean research (Parsons et al 2015). This is especially salient given the emerging evidence that some baleen whales have limited potential for vessel avoidance (McKenna et al 2015).

Historically, Mayumba Marine Park was the only designated MPA within the Gabon EEZ: confined to a 15 x 60 km strip of coastal waters to the far south of the Gabonese EEZ. Typically, small protected areas offer limited conservation benefits (Gaines et al., 2010) particularly to mobile species. A recent comprehensive marine spatial planning review has been made of Gabon’s territorial waters which integrated data from this analysis. This review has led to, approximately 23% of Gabon's territorial waters and EEZ being designated as MPAs, in which commercial fishing will be excluded. For leatherback turtles, this is likely to result in increased protection of inter-nesting at-sea habitat in waters adjacent to Mayumba National Park, in near-shore waters to the south of Port Gentil and to the north, at Pongara (Fig. 5). Indeed, associated management strategies protecting marine habitats and improving fisheries management, including improved surveillance and enforcement of fisheries, as well as designation of exclusion zones around maritime oil and gas infrastructure, likely already influence some vessel movements in key areas identified in this study. Ultimately, with increased spatio-temporal understanding of threat (gleaned from continued collection and analysis of vessel movements) and species/vessel interactions (collected by way of boat observer programs and post-mortems), together with better temporal understanding of impacts (e.g. deployment of season-specific gear types), MPA design and management strategies may be tailored and fine-tuned to deliver a holistic network of protected areas that provide protection for a suit of Gabon's biodiversity rich marine species.

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Legends

Fig. 1. Location data (black circles) of satellite tracked inter-nesting leatherback turtles tracked from, (a) Pongara National Park (*n* = 18) and (b) Mayumba National Park (*n* = 14). Tagging locations (white stars). (c) Modelled leatherback turtle density at-sea October-April. Densities (turtles 100 km^{-2} apportioned by percentiles) are drawn in accordance with the figure legend. 200 m continental shelf isobath (broken line) and EEZ maritime boundaries (broken line polygon). In part (c) coastal National Parks (dark-grey polygons) and reserves (mid-grey polygons) and the ports of Libreville and Port Gentil are labelled. Mayumba National Park (Marine Protected Area (MPA)), broken white polygon. Part (c) is located according to the inset. All parts drawn to differing spatial scales. Map drawn to Projected Coordinate System: Africa Albers Equal Area Conic.

Fig. 2. Density mapping of fisheries activity derived from Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data. (a-d) VMS data for leatherback nesting seasons 2010/11 and 2011/12. A speed rule was applied to distinguish fishing from steaming or near-stationery movement (Witt & Godley 2007); only data with speeds ≥ 1 or ≤ 5 knots were retained. (e-h) AIS data for leatherback nesting seasons 2012/13 and 2013/14. A speed rule was applied to remove near-stationery movement; only data with speeds ≥ 1 knot were retained. For each dataset, data for the complete nesting season (a,e) were apportioned into three seasonal groups: (b,f) October and November, (c,g) December to February and (d,h) March and April. Location data were summarised (counts) to a 10 x 10 km resolution raster with only the first location per day per cell being counted. Annual averaged seasonal density rasters were then divided by the respective numbers of days of the season. This provided a surface that described the average (mean) number of unique vessels day^{-1} within each 10 x 10 km raster pixel. Parts (a,b,c,d) and (e,f,g,h) are drawn to differing spatial scales. All other map features are drawn and labelled in accordance with Fig. 1. Map drawn to Projected Coordinate System: Africa Albers Equal Area Conic.

Fig. 3. Density mapping of vessel activity categorised as, (a-d) oil support vessels, including tankers carrying crude/refined oil and other petrochemical related products, (e-h) seismic research vessels and (i-l) cargo vessels, derived from Automatic Identification System (AIS) data for leatherback nesting seasons 2012/13 and 2013/14. A speed rule was applied to remove near-stationery movement; only data with speeds ≥ 1 knot were retained. Data for the complete nesting season (a,e,i) were then apportioned into three seasonal groups: (b,f,j) October and November, (c,g,k) December to February and (d,h,i) March and April. Location data were summarised (counts) to a 10 x 10 km resolution raster with only the first location per day per cell being counted. Annual averaged seasonal density rasters were then divided by the respective numbers of days of the season. This provided a surface that described the average (mean) number of unique vessels day^{-1} within each 10 x 10 km raster pixel. All parts drawn to the same spatial scale. All other map features are drawn and labelled in accordance with Fig. 1. Map drawn to Projected Coordinate System: Africa Albers Equal Area Conic.

Fig. 4. Cumulative seasonal vessel densities (a,c,e,g). Vessel density rasters were re-scaled 0-1 and summed. Threat index for inter-nesting leatherback turtles (b,d,f,h). Cumulative vessel density rasters were multiplied by leatherback density rasters. To provide for data at the same spatial resolution leatherback turtle at-sea density raster were re-sampled to the same resolution (10 x 10 km) as the VMS and AIS layers using bilinear interpolation. Data for the complete nesting season (a,b) were then apportioned into three seasonal groups: (c,d) October and November, (e,f) December to February and (g,h) March and April. All parts drawn to the same spatial scale. All other map features are drawn and labelled in accordance with Fig. 1. Map drawn to Projected Coordinate System: Africa Albers Equal Area Conic.

Fig. 5. Leatherback turtle density at-sea and Marine Protected Areas. Leatherback turtle densities (turtles 100 km^{-2} apportioned by percentiles: October-April) are drawn in accordance with the figure legend. Mayumba National Park (Marine Protected Area (MPA)), broken white polygon, all other MPAs, black hatched polygons. All other map features are drawn and labelled

in accordance with Fig. 1. Map drawn to Projected Coordinate System: Africa Albers Equal Area Conic.

Figure(s)

Fig. 1.

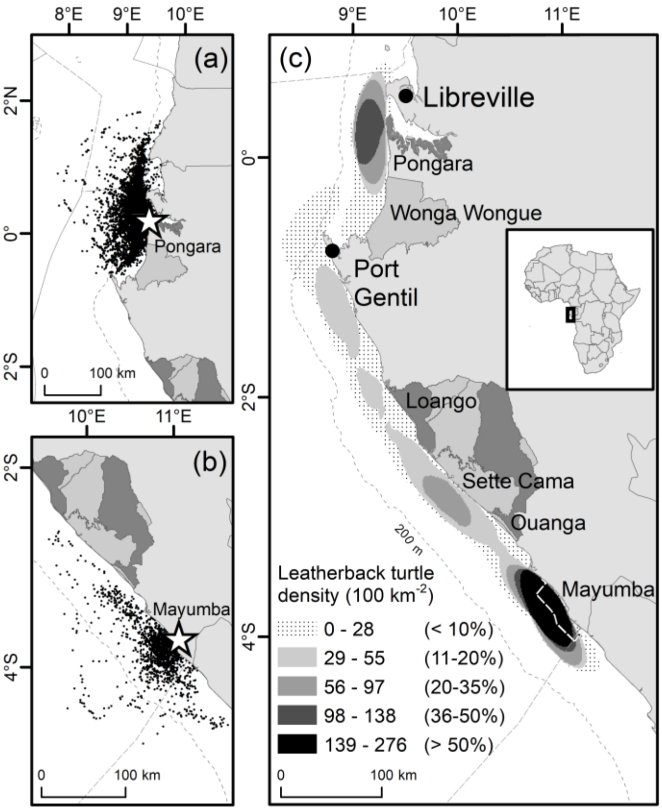


Fig. 2.

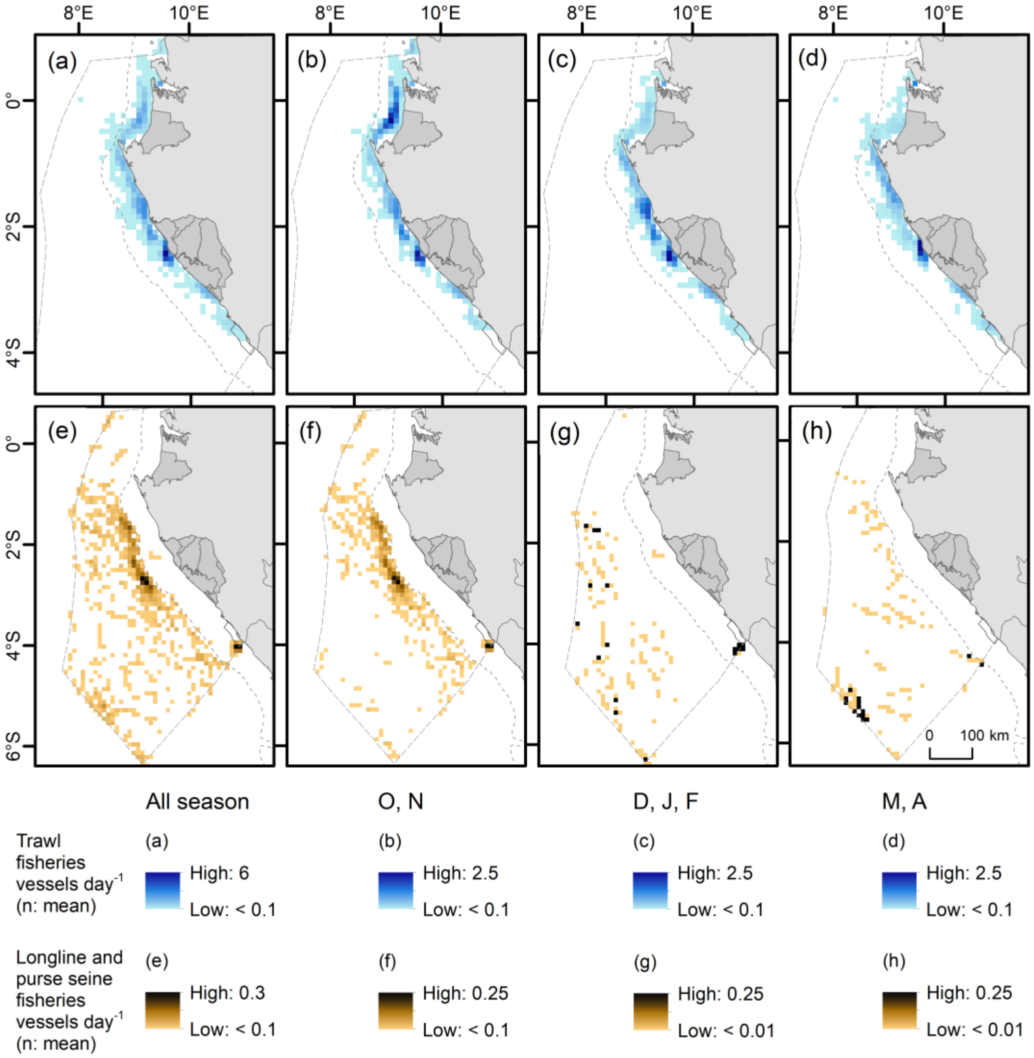

8°E
10°E
0°
2°S
4°S
6°S
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
0
100 km
All season
O, N
D, J, F
M, A
Trawl fisheries vessels day⁻¹ (n: mean)
(a) High: 6 Low: < 0.1
(b) High: 2.5 Low: < 0.1
(c) High: 2.5 Low: < 0.1
(d) High: 2.5 Low: < 0.1
Longline and purse seine fisheries vessels day⁻¹ (n: mean)
(e) High: 0.3 Low: < 0.1
(f) High: 0.25 Low: < 0.1
(g) High: 0.25 Low: < 0.01
(h) High: 0.25 Low: < 0.01

Fig. 3.

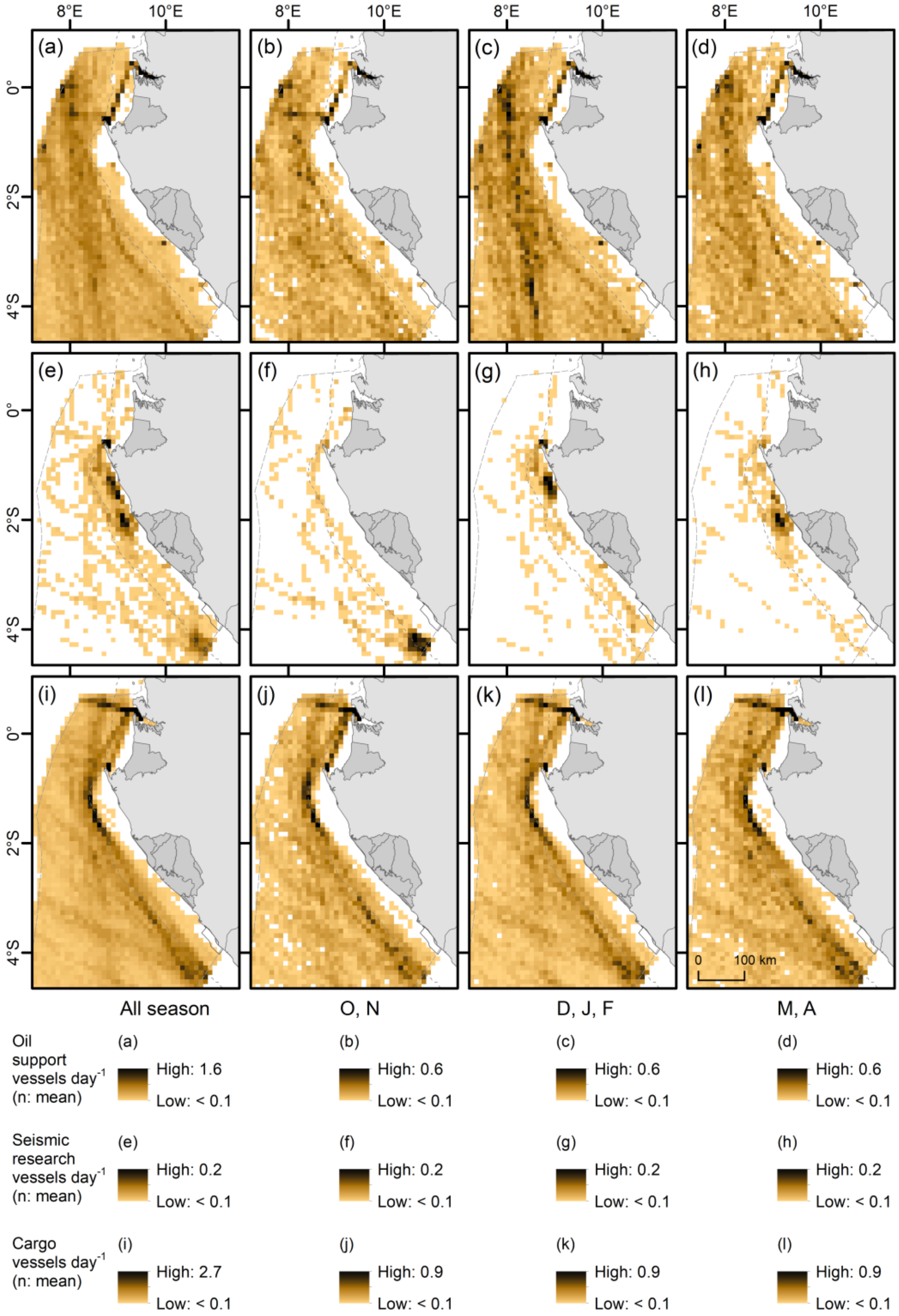
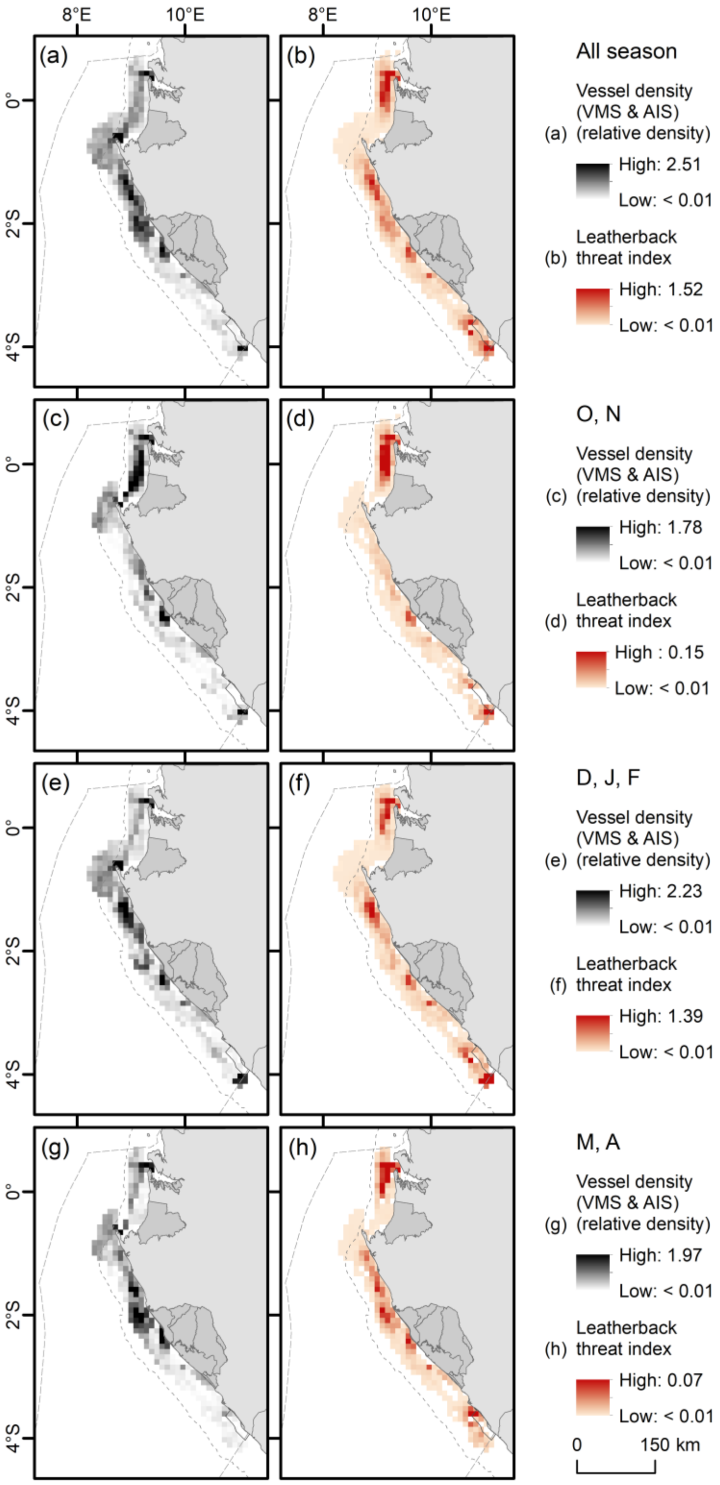
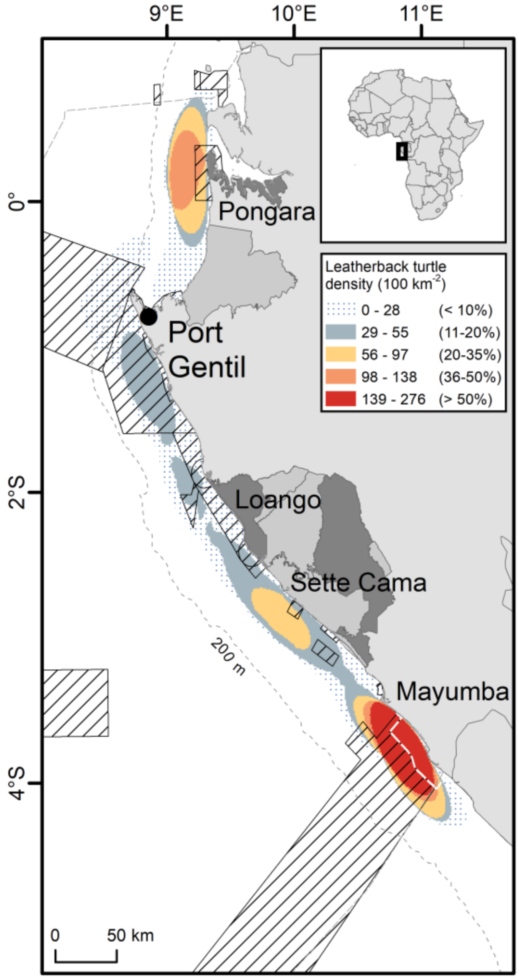

8°E
10°E
0°
2°S
4°S
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
0
100 km
All season
O, N
D, J, F
M, A
Oil support vessels day^{-1} (n: mean)
(a) High: 1.6 Low: < 0.1
(b) High: 0.6 Low: < 0.1
(c) High: 0.6 Low: < 0.1
(d) High: 0.6 Low: < 0.1
Seismic research vessels day^{-1} (n: mean)
(e) High: 0.2 Low: < 0.1
(f) High: 0.2 Low: < 0.1
(g) High: 0.2 Low: < 0.1
(h) High: 0.2 Low: < 0.1
Cargo vessels day^{-1} (n: mean)
(i) High: 2.7 Low: < 0.1
(j) High: 0.9 Low: < 0.1
(k) High: 0.9 Low: < 0.1
(l) High: 0.9 Low: < 0.1

Fig. 4.



8°E
10°E
8°E
10°E
0°
2°S
4°S
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
All season
Vessel density
(VMS & AIS)
(a) (relative density)
High: 2.51
Low: < 0.01
Leatherback
(b) threat index
High: 1.52
Low: < 0.01
O, N
Vessel density
(VMS & AIS)
(c) (relative density)
High: 1.78
Low: < 0.01
Leatherback
(d) threat index
High : 0.15
Low: < 0.01
D, J, F
Vessel density
(VMS & AIS)
(e) (relative density)
High: 2.23
Low: < 0.01
Leatherback
(f) threat index
High: 1.39
Low: < 0.01
M, A
Vessel density
(VMS & AIS)
(g) (relative density)
High: 1.97
Low: < 0.01
Leatherback
(h) threat index
High: 0.07
Low: < 0.01
0
150 km

Fig. 5.


9°E
10°E
11°E
0°
2°S
4°S
Pongara
Port Gentil
Loango
Sette Cama
Mayumba
200 m
0
50 km
Leatherback turtle density (100 km-2)
0 - 28 (< 10%)
29 - 55 (11-20%)
56 - 97 (20-35%)
98 - 138 (36-50%)
139 - 276 (> 50%)

Supplementary material

Table A.1. Aerial survey schedule for the Gabonese coast 2002/03, 2005/06 and 2006/07.

Nesting season	**Survey**	**Aerial survey dates**	
		Start	**End**
2002/03	1	2003-01-11	2003-01-12
	2	2003-01-25	2003-01-26
2005/06	1	2005-12-08	2005-12-09
	2	2006-01-23	2006-01-25
	3	2006-02-21	2006-02-22
2006/07	1	2006-12-12	2006-12-14
	2	2007-01-25	2007-01-26
	3	2007-02-23	2007-02-24

Table A.2. Summary of PTT data for female leatherback turtles, detailing: PTT Id., nesting season, release location, deployment date, inter-nesting periods (n), PTT manufacturer and model.

Id	PTT	Nesting season	Release location	Deployment date	Inter-nesting periods (n)	Inter-nesting duration (mean) (days)	PTT make	Model
1	57666	2005/06	M	2005-12-10	1	11	Sirtrack	KiwiSat 101
2	57383		M	2005-12-11	0	no data	Sirtrack	KiwiSat 101
3	57381		M	2006-02-23	0	no data	Sirtrack	KiwiSat 101
4	57378		M	2006-02-24	1	10	Sirtrack	KiwiSat 101
5	57390		M	2006-02-24	1	13	Sirtrack	KiwiSat 101
6	65693		M	2006-03-09	0	no data	SMRU*	SRDL
7	57663		M	2006-03-19	0	no data	Sirtrack	KiwiSat 101
8	65694		M	2006-03-22	1	11	SMRU*	SRDL
9	68562	2006/07	M	2007-02-03	2	10	SMRU*	SRDL
10	68563		M	2007-02-09	1	11	SMRU*	SRDL
11	80621	2007/08	M	2008-02-12	0	no data	Sirtrack	KiwiSat 202
12	80622		M	2008-02-12	1	7	Sirtrack	KiwiSat 202
13	80623		M	2008-02-12	2	10	Sirtrack	KiwiSat 202
14	80620		M	2008-02-12	2	12	Sirtrack	KiwiSat 202
15	80624		M	2008-02-12	1	11	Sirtrack	KiwiSat 202
16	89072	2008/09	P	2008-12-08	3	12	Wildlife Computers	MK10-AF
17	89071		P	2008-12-09	6	12	Wildlife Computers	MK10-AF
18	89075		P	2008-12-11	5	11	Wildlife Computers	MK10-A
19	89073		P	2008-12-15	4	11	Wildlife Computers	MK10-AF
20	89074		P	2008-12-16	3	10	Wildlife Computers	MK10-AF
21	89076		P	2008-12-16	7	10	Wildlife Computers	MK10-A
22	92577		M	2009-02-18	3	10	Wildlife Computers	MK10-A
23	92578		M	2009-02-18	2	10	Wildlife Computers	MK10-A
24	92579		M	2009-02-21	1	10	Wildlife Computers	MK10-A
25	92580		M	2009-02-21	1	12	Wildlife Computers	MK10-A
26	92581	2009/10	P	2009-12-07	5	11	Wildlife Computers	MK10-A
27	92582		P	2009-12-07	7	10	Wildlife Computers	MK10-A
28	122425	2012/13	P	2012-10-25	7	10	Wildlife Computers	SPLASH10-AF
29	122426		P	2012-10-26	6	11	Wildlife Computers	SPLASH10-AF
30	122427		P	2012-10-26	7	11	Wildlife Computers	SPLASH10-AF
31	122428		P	2012-10-27	7	10	Wildlife Computers	SPLASH10-AF
32	122429		P	2012-10-27	6	9	Wildlife Computers	SPLASH10-AF
33	122430		P	2012-10-28	1	9	Wildlife Computers	SPLASH10-AF
34	122431		P	2012-10-28	5	10	Wildlife Computers	SPLASH10-AF
35	122432		P	2012-10-28	7	11	Wildlife Computers	SPLASH10-AF
36	122433		P	2012-10-28	8	10	Wildlife Computers	SPLASH10-AF
37	122434		P	2012-10-28	7	11	Wildlife Computers	SPLASH10-AF
				mean	3	10		
				total	121			

* Sea Mammal Research Unit

Table A.3. Summary of output from Wilcoxon test of semi-major, semi-minor and offshore distance for leatherback turtles between the nesting locations of Pongara and Mayumba National Parks.

Ellipse metric	**Wilcoxon z score**	**p value**	**Median value (km)**	
			Pongara	**Mayumba**
Semi-major axis length	1.29	0.20	36.25	45.19
Semi-minor axis length	0.23	0.82	16.74	17.80
Offshore distance	0.91	0.36	16.37	19.03