Going the extra mile: Ground-based monitoring of olive ridley turtles reveals Gabon hosts the largest rookery in the Atlantic

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ABSTRACT

The management of widely dispersed marine vertebrates can be facilitated by better understanding their distribution, density, population trends and threats. Unfortunately, for some populations of sea turtle spatial and temporal data are often lacking, particularly along the Atlantic coast of Africa, a region which is considered globally important. Here we combined spatially limited monitoring data from four nesting beaches over seven seasons with an extensive ground-based coastal survey that covered 585 km of Gabon's Atlantic coast, to provide the first population assessment for the olive ridley turtle *Lepidochelys olivacea*. This species is currently classified as data deficient by the IUCN in the eastern Atlantic and so is considered a regional conservation priority. Whilst the logistics required to undertake such a comprehensive ground-based census were complicated, the method proved extremely effective in providing population estimates for a widely dispersed marine vertebrate and demonstrates the importance of focusing beyond intensively monitored beaches. In particular, our findings reveal that the presence of nesting activity spans almost the entirety of Gabon's coast, the density of which subsequently reveals that Gabon hosts one of the most important olive ridley rookeries in the Atlantic (2370–9814 clutches, approximating to 948–5452 breeding females per annum and a total estimate of 1422–8178 breeding females), with a significant proportion, 81 ± 3.5% (mean ± 1 S.D.) of total nesting effort occurring within protected areas. These findings thus complement our existing knowledge base and further emphasise the regional and global importance of Gabon's nesting sea turtle populations.

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1. Introduction

Many large marine species including sharks, sea turtles and cetaceans are considered to be of conservation concern throughout their range due to a long history of human exploitation (Jackson

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et al., 2001). Conservation efforts for such species can, however, be complicated by life history characteristics such as extended life spans and highly migratory life cycles that carry them across jurisdictional boundaries and international waters (Kappes et al., 2010; Luschi et al., 2003; Robinson et al., 2012; Shaffer et al., 2006). Effective management thus requires a greater understanding of the seasonality of life history characteristics and their distribution and spatial ecology (Maxwell et al., 2013; Rosenbaum et al., 2014; Wallace et al., 2010; Young et al., 2015).

Sea turtles have been subject to multiple anthropogenic pressures, such as direct and indirect take in fisheries and habitat degradation that have resulted in a reduction of global populations to a fraction of their former size (McClenachan et al., 2006). However, some populations are now recovering, raising hopes that relatively simple but sustained conservation measures such as protection of females and eggs at nesting beaches and changes in fishing practices can be effective (Godgenger et al., 2009; Gratiot et al., 2006; Weber et al., 2014; Witt et al., 2011). Whilst in non-breeding years adult sea turtles can disperse over large oceanic areas, a proportion of adults seasonally aggregate at a small number of major rookeries (Luschi et al., 2003) where nesting can be enumerated as an index of population size using a range of methods (Gerrodette and Taylor, 1999; Whiting et al., 2014). Annual breeding numbers fluctuate over time and individual monitoring sites may vary significantly among years due to environmental factors (Broderick et al., 2001). Long-term monitoring is therefore essential to establish population trends (Jackson et al., 2008) and to provide detailed knowledge on the relative density of nesting and habitat use that can aid targeted conservation efforts (Mazaris et al., 2014), such as the designation of marine protected areas (MPAs).

The most common method to enumerate nesting sea turtles is using ground-derived counts of the number of nests laid in a particular season (e.g. Stewart et al., 2011; Weber et al., 2014; Witherington et al., 2009), though aerial surveys are increasingly being employed to monitor sea turtle populations (e.g. McGowan et al., 2008; Tröeng et al., 2004; Witt et al., 2009). Both approaches have their advantages and disadvantages (Schroeder and Murphy, 1999). The former approach in particular is often labour intensive, as the nesting season for most species of sea turtle can last for many months (Miller, 1997). In addition, efforts can often be hindered by the distant and dispersed nature of nesting beaches (e.g. located in remote and inaccessible areas), leading to an approach where only a limited number of nesting beaches are monitored in detail and/or consistently each season. In contrast, aerial surveys allow for data collection over considerable spatial scales (i.e. 100's of kilometres) and so can facilitate more meaningful estimates of population size and trends, as well as increasing our understanding and knowledge of nesting habitat preference, threats, and the efficacy of protected areas (Witt et al., 2009).

Indeed, aerial surveys have proved highly effective for monitoring the status of leatherback turtles (Dermochelys coriacea) in Gabon, identifying its coastline as the world's largest rookery for the species, with an estimated 5865–20,499 nesting females per annum (Witt et al., 2009). However, aerial surveys are unlikely to produce such reliable estimates for Gabon's second most numerous nesting sea turtle, the olive ridley (Lepidochelys olivacea), as its smaller body size and mass mean it leaves smaller, fainter tracks that are more difficult to spot from the air. In addition, similar habitat preferences, overlapping nesting seasons, and the density of leatherback turtles in some regions often result in olive ridley tracks being covered, hampering our ability to generate robust nesting estimates from aerial surveys. As such, the current status of this rookery is less certain.

Consequently, given the limitations of aerial survey data and evidence that ground-based surveys are better able to detect evidence of olive ridley nesting activity, we conducted an extensive coastal survey along 585 km of Gabon's coast. This represents the first ground-based national survey to cover extensive areas of the coast beyond intensively monitored beaches. The specific aims of the survey were to: (1) establish whether such a coastal survey would be feasible and describe the overall spatial patterns of nesting; (2) estimate the number of nests laid each season by combining monitoring data collected from four sites over seven seasons with the coastal survey to identify temporal trends, and so determine the number of nesting females to derive a population estimate for the Gabon rookery; and (3) provide a preliminary overview of the spatial adequacy of Gabon's existing protected area network for this species.

2. Material and methods

2.1. Ground-based coastal surveys

Between 28 October and 27 November 2013 two coastal transects were conducted over 585 km of Gabon's coastline from north to south (Fig. 1). These were timed to encompass the early to mid-part of olive ridley nesting activity in the region (September–March; Godgenger et al., 2009). The first transect (28 October–1 November 2013; $n = 5$ days) was 113 km in length and started in Pointe Denis in Pongara National Park and ended south in Wonga Wongue Presidential Reserve where the beach transitions into mangrove habitat, an area considered unsuitable for nesting olive ridley turtles (Fig. 1). The second transect (14 November–27 November 2013; $n = 14$ days) was 471 km in length and started at Cap Lopez close to Port Gentil, and ended at Nyafessa lagoon mouth in Mayumba National Park approximately 8 km from the border between Gabon and the Republic of Congo (Fig. 1).

During each transect, the location of visible olive ridley activity on the beach (defined as either a nest where a turtle successfully deposits a clutch of eggs, or a non-nesting emergence where females emerge onto the nesting beach but do not subsequently deposit a clutch) was recorded using two global positioning system (GPS) hand-held receivers (models: Garmin GPSMAP 62; and Garmin eTrex 10) by a team comprising a minimum of two people. A minimum of two people was used on each survey to ensure that the total width of beach available for nesting was surveyed for signs of visible activity, and to minimise observer error that might otherwise have resulted from surveyor fatigue. For each transect, we followed the survey protocol for ground-based counts devised by Schroeder and Murphy (1999) and assigned each nesting activity an estimated age (in days). In addition to nesting activity we also recorded occurrences of stranded turtles washed ashore dead or alive, and their location relative to Gabon's network of coastal protected areas.

2.2. Estimating seasonal patterns of nesting effort

2.2.1. Nesting beach monitoring data

We used daily ground counts of nests recorded by field patrols conducted at dawn that record only the previous night's activity from four monitoring locations (Pointe Denis, Gamba, Bame and Nyafessa; Fig. 1) that have been monitored each sea turtle nesting season from 2006/2007 to 2012/2013 ($n = 7$ seasons). These sites are situated along the north, central and southern coast of Gabon (Fig. 1) and so are likely to provide the most robust representation of seasonal patterns of nesting effort to date.

Existing survey efforts, however, have largely been designed to monitor leatherback turtles, which have a seasonality (November–March) later than that of olive ridley sea turtles (September–March; Godgenger et al., 2009). For example, only $0.12 \pm 0.31\%$ (CI: 0.23–0.35; $n = 7$) and $19 \pm 17\%$ (CI: 13–32; $n = 7$) of
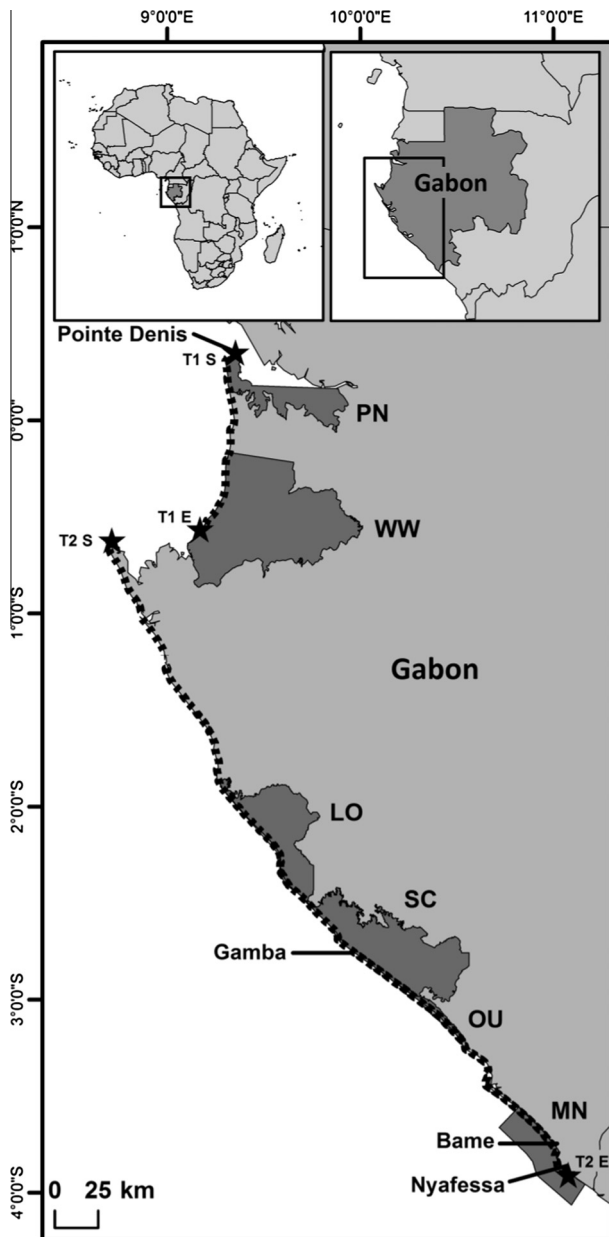
Fig. 1. National Parks and Reserves of Gabon bordering the Atlantic Ocean. Dashed black lines indicate the location of coastal transects, filled stars indicate the start and end locations of each transect (transect 1: T1 S: start, and T1 E: end; transect 2: T2 S: start, and T2 E: end). Labelled regions (Pointe Denis, Gamba, Bame and Nyafessa) indicate the location of the monitoring data used to derive seasonal patterns of nesting effort. Labels: Pongara National Park (PN), Wonga Wongue Presidential Reserve (WW), Loango National Park (LO), Sette Cama Reserve (SC), Ouangu Reserve (OU) and Mayumba National Park (MN).

September and October, respectively, have been monitored each season, in contrast to November through March, where on average >60% of days in each month has been monitored each season (Fig. S1). Therefore, whilst existing monitoring efforts have likely encountered the peak of olive ridley nesting activity each year, coverage of the beginning of each olive ridley turtle nesting season was for the large part absent; as such, it was necessary to estimate nesting numbers for the early part of the season at each monitoring location each year.

2.2.2. Constructing seasonal curves

We first assigned the total number of monitoring days and daily ground counts of observed nests at each of the four monitoring

locations into half-month survey bins for each nesting season (n = 24 survey bins). Half-month survey bins were selected to minimise day-to-day variance in nesting numbers and allow us to generate meaningful seasonal patterns. To account for missing data when daily ground counts were not undertaken due to bad weather, public holidays or logistical constraints we used linear interpolation (Godley et al., 2001). We then constructed frequency distributions for each monitoring location with numbers for each half-month survey bin based on the mean proportion of seasonal maximum, using only half-month bins with ≥10 days monitoring. The mean proportion of the maximum recorded in each half-month survey bin at each monitoring location was thus taken to be the mean of the proportions recorded in each nesting season. For example, the half-month proportion between 1 and 15 November was the mean of the proportions of all seasons 2006–2012 and so incorporated any temporal variability in the seasonality of nesting.

At each of the four monitoring locations, the start of monitoring ranged between 30 September and 3 December (mean date over the seven seasons: 26 October, 13 November, 9 November and 27 October at Pointe Denis, Gamba, Bame and Nyafessa, respectively), and so the beginning of the olive ridley nesting season has not been observed to date (Fig. S1). Therefore, we reconstructed the three half-month survey bins commencing 1 September, 16 September and 1 October (i.e. the beginning of the nesting season) by attributing a value of 50% of temporally subsequent half-month bin. We used 50% iteratively as this produced frequency distributions that corresponded closely to those modelled for olive ridley rookeries subject to monitoring in neighbouring Republic of Congo and in French Guiana, where patterns of nesting effort are typically close to symmetrical around the peak, with the end of the nesting season sharper than the beginning (Godgenger et al., 2009; Gratiot et al., 2006). These four frequency distributions (one for each monitoring site) were then used to model the number of nests in each half-month survey bin each season. We were then able to derive seasonal curves based on the mean proportion of seasonal total in each half month-survey bin to represent patterns of nesting effort at each monitoring location.

2.3. Generating seasonal estimates

To generate an estimate of the total number of olive ridleys nesting along the coast in 2013/2014 we divided each transect into survey sections of 5 km. For each 5 km survey section the presence of nesting activity (excluding non-nesting emergences) was assigned to its centre point and summed. Given that a range of environmental factors can complicate nest ageing (e.g. daily tidal patterns, wave activity and exposure to wind and rain) we used only nests classified as ≤1, 2 and 3 days old in the subsequent analyses. For each of these three nest age classes we then estimated the total number of nests in each 5 km survey section by first scaling the total number of observed nests by the number of days during which these nests were laid. In order to incorporate any spatial variation in both the seasonality and proportion of nesting effort we then multiplied this value by the mean half-month proportion of the seasonal total derived from the frequency distributions generated for the nearest monitored beach. We then summed all survey bins within each of the three nest age classes, thus generating three seasonal estimates of the total number of nests laid in 2013/2014 (hereafter referred to as estimates of total nesting effort).

2.4. Spatial patterns of nesting activity

To illustrate the relative spatial distribution of olive ridley nesting activity in 2013/2014 and so highlight potentially important areas for targeted conservation and monitoring efforts, we aggregated the number of nests in each 5 km survey section for each

of the three estimates of total nesting effort to a 0.1 degree latitudinal resolution, equivalent to approximately 11 km at the equator (which divides Gabon). We then used waveform repeatability analysis (Lee, 2006) to determine the spatial consistency of olive ridley activity along the Gabon coast across each of the three estimates (Witt et al., 2009). Each waveform repeatability analysis calculates the correlation of multiple coefficients (CMC). CMC may be interpreted in the same manner as Pearson and Spearman correlation coefficients (Lee, 2006) where 1.0 represents a perfect significant positive correlation, −1.0 represents a perfect negative correlation, and values tending towards 0 suggest no linear relationship (Lee, 2006). For each of the three estimates of total nesting effort we also calculated the proportion of nests occurring within National Parks and Reserves (i.e. protected areas) by identifying the 5 km survey bins that overlap with these areas. We used only survey bins occurring completely within protected areas and so provide a conservative estimate of nesting within each of the protected areas (Fig. 1), thus complementing our knowledge base on the efficacy of this network for sea turtles in the region.

2.5. Annual trends in nesting effort

Given that the coastal transect provides an overview of the spatial patterns of nesting in 2013/2014, we scaled up olive ridley turtle nesting to produce a Gabon-wide estimate of nesting for each season between 2006/2007 and 2012/2013. To do this we calculated the proportion of nesting activity each monitoring location received in 2013/2014 for each of the three estimates of total nesting effort, using only survey bins occurring completely within the four monitored areas. From these values we then derived minimum and maximum estimates of total nesting effort for the entire coastline each season by dividing the total number of nests at monitored sites each season by the sum total of the proportion of nesting activity at monitored locations generated for each of the three estimates of total nesting effort.

3. Results

3.1. Ground-based coastal surveys

Of the 786 activities recorded during the coastal transects, 30 (4%) were assigned as non-nesting emergences, and 756 (96%) were assigned as emergences that resulted in the deposition of a clutch. Additionally, a total of 23 strandings (*n* = 21 dead, *n* = 2 alive) were observed along the entire coastal transect, the majority of which were observed between −0.5°S and −3.5°S (Fig. S2).

3.2. Seasonal patterns of nesting effort

Reconstruction of nesting effort each season (Table 1) indicates that September and October account for approximately 5 ± 1.6% (CI: 4.3–5.4; *n* = 28) and 21 ± 7.8% (CI: 18.2–23.9; *n* = 28) of total nesting effort respectively (mean proportion over seven seasons: 7%, 5%, 5%, and 3% in September, and 29%, 21%, 19%, and 15% in October for Pointe Denis, Gamba, Bame and Nyafessa respectively). Thus, based on these reconstructed nesting data, nesting occurs approximately between 1 September and 16 March across all four monitoring locations (Fig. 2). There was, however, a slight shift with latitude in both the peak date, and proportion of nesting effort across all four monitoring locations; from the week commencing 16 October for Pointe Denis in the north (mean proportion: 17 ± 3.9% CI: 14.6–20.5; *n* = 7), 1 November for Gamba located along the central coast (mean proportion: 19 ± 10.7% CI: 11–26.9; *n* = 7), to the 16 November for Bame (mean proportion: 21 ± 5.7% CI: 16.6–25.1; *n* = 7) and Nyafessa (mean proportion: 22 ± 6.0%

Table 1
Total number of observed, interpolated and modelled nests for each of the four monitoring locations each season.

Season	Pointe Denis	Gamba	Bame	Nyafessa	Total
2006/2007					
Observed	22	56	28	71	177
Interpolated	23	62	41	112	238
Modelled	44	115	80	183	421
2007/2008					
Observed	68	57	36	165	326
Interpolated	85	129	48	214	477
Modelled	93	214	85	232	624
2008/2009					
Observed	41	11	12	57	121
Interpolated	50	12	14	92	168
Modelled	58	22	42	93	215
2009/2010					
Observed	51	32	42	160	285
Interpolated	54	42	48	180	324
Modelled	64	53	66	208	391
2010/2011					
Observed	30	55	89	218	392
Interpolated	33	59	99	254	445
Modelled	38	61	112	278	489
2011/2012					
Observed	120	32	60	320	532
Interpolated	133	39	62	335	569
Modelled	141	52	69	358	620
2012/2013					
Observed	43	28	88	372	531
Interpolated	53	30	101	435	619
Modelled	101	60	126	526	813

Notes: Observed nests are based on the number of nests recorded from daily ground counts, interpolated nests (rounded to nearest whole nest) are based on linear interpolation to account for days when daily ground counts were not undertaken, and modelled nests (rounded to nearest whole nest) represent the total number of estimated nesting activities corrected to account for the beginning of each nesting season when daily ground counts were not undertaken.

CI:17.3–26.3; *n* = 7) located in the south (Figs. 1 and 2). By extracting the mean date of peak nesting from each half month bin assigned as the seasonal peak for each monitoring location each season we confirmed that there was a correlation between peak date of nesting and latitude (Fig. 3).

3.3. Seasonal estimates

Extrapolation of ground counts derived from the coastal transect resulted in estimates for the total number of nests laid in Gabon in 2013/2014 that ranged between 8662 and 14,033 nests. Of the three estimates of total nesting effort, including only 5 km survey bins with nests classified as ⩽1 day old produced higher estimates (14,033 nests; *n* = 52 survey bins) compared to estimates based on survey bins including nests classified as ⩽2 days (9814 nests; *n* = 57 survey bins) and ⩽3 days old (8662 nests; *n* = 68 survey bins). Comparisons of the mean number of estimated nests at each monitoring location each season derived using this extrapolation method on raw data from daily ground counts collected in October–November (coastal survey transect period) revealed that this approach was generally robust, with a positive linear relationship between the actual and estimated number of nests across the four monitoring locations (*R*² 0.68–0.98; Fig. S3).

3.4. Spatial patterns of nesting activity

The coastal transects revealed that olive ridley nesting activity spanned almost the entire coast with only a few survey bins where nests were not observed during the survey period (Fig. 4a).
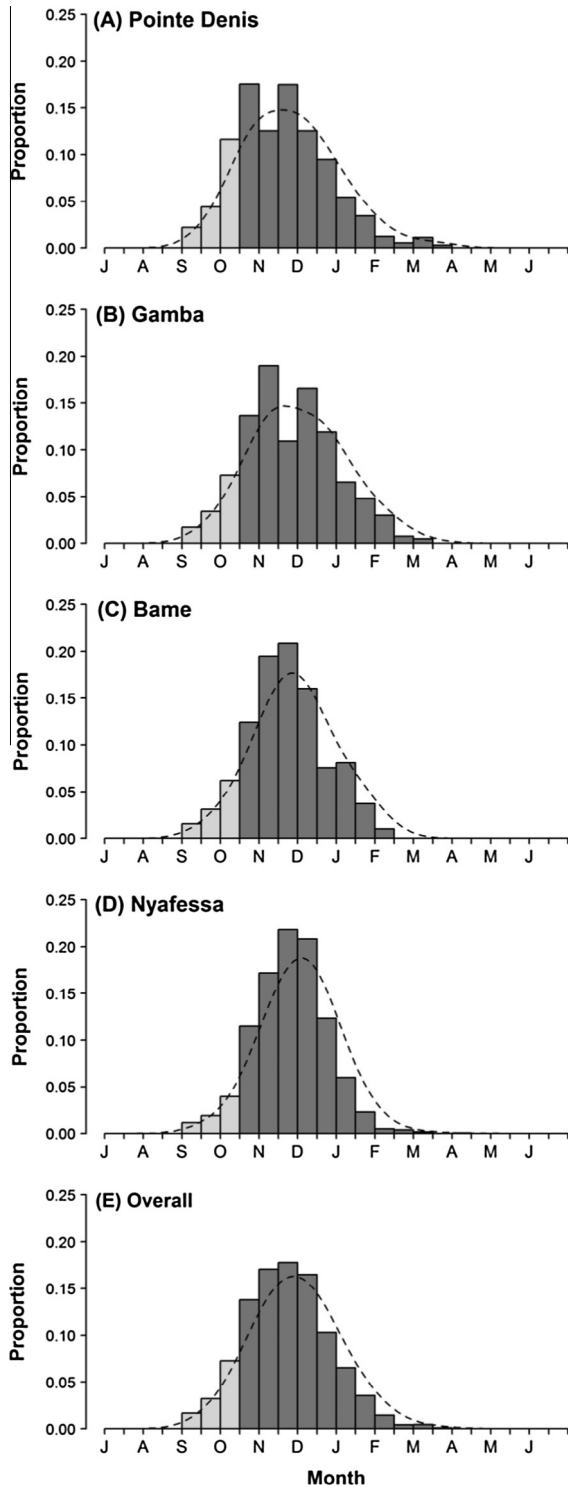
Fig. 2. Seasonal patterns of nesting effort. Mean proportion of seasonal total in each half month survey bin for: (A) Pointe Denis; (B) Gamba; (C) Bame; (D) Nyafessa; relative to (E) overall curve for all four monitoring locations combined. Light grey bars indicate half month bins that have been reconstructed and dark grey bars indicate those half month bins that are derived from long-term monitoring data. Dashed line represents smoothed estimate of nesting activity through time (using ksmooth; R Core Team, 2014 where span equals 3).

Waveform repeatability analysis indicated that there was a strong correlation between spatial patterns of olive ridley nesting across the three estimates of total nesting effort (mean CMC: 0.96 ± 0.02 range: 0.94–0.99). Data revealed that the southern extent of Gabon's coastline received the highest densities of nesting activity,

specifically between 2°S and 3.9°S which accounts for 89 ± 3.6% (CI: 85–93; $n = 3$) of total nesting effort (Fig. 4b). Based on the three estimates of total nesting effort for 2013/2014, National Parks and Reserves that stretch along approximately 375 km (64%) of the surveyed coastline received 81 ± 3.5% (CI: 77–85; $n = 3$) of olive ridley turtle nesting effort. Of the six protected areas that border the coast, Sette Cama and Ouangu Reserve (located between 2.5°S and 3.2°S; Fig. 4b) hosted the greatest proportion of nesting activity with 23 ± 0.29% (CI: 22–23; $n = 3$) and 23 ± 1.5% (CI: 21–25; $n = 3$), along 82 km (14%) and 42 km (7%) of the surveyed coastline, respectively (Fig. 5).

### 3.5. Annual trends in nesting effort

Whilst patterns of nesting effort have fluctuated at Pointe Denis, Gamba and Bame with mean annual growth rates of 19%, −7%, and 8% respectively, nesting effort at Nyafessa has increased by an average of 27% annually (i.e. equivalent to a 3-fold increase), which consequently, has contributed to an overall mean annual growth rate in total nesting effort of 13.3% (i.e. equivalent to a 2-fold increase) across these four monitoring locations since 2006/2007 (Fig. 6a). Thus, using data on spatial patterns of nesting effort in 2013/2014 to scale up nesting effort along the entire coast of Gabon suggests that upper and lower estimates of the number of nests that were laid annually between 2006/2007 and 2013/2014 ranged between 1887 and 14,033 nests, with median estimates ranging between 2370 and 9814 (Fig. 6b).

4. Discussion

The management of widely dispersed marine species can be facilitated by better understanding their distribution, density, population trends and threats. For sea turtles in particular, there have been increasing calls for a greater emphasis on identifying temporal trends and developing spatial data at a local and regional scale to help inform *IUCN Red List* assessments (Seminoff and Shanker, 2008). Unfortunately, for many regional management units, the development of these data is often hindered by a lack of recent and/or robust data from known nesting aggregations (Mazaris et al., 2014; Wallace et al., 2010). In particular, research over the last few decades has revealed the Atlantic coast of Africa as a globally important region for sea turtles, hosting several major nesting aggregations (Fretey, 2001), yet this importance is not well captured in the peer-reviewed scientific literature. For example, olive
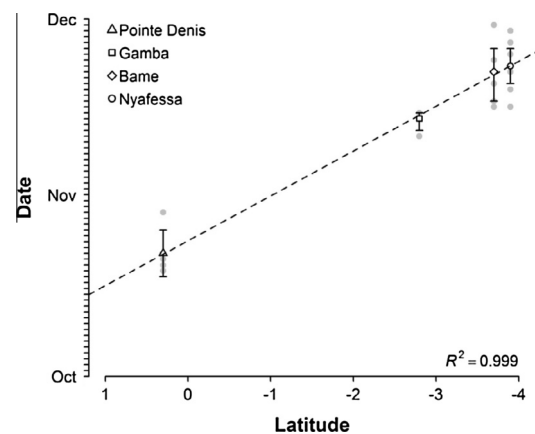

Fig. 3. Mean date of peak nesting extracted from raw ground count data for the dates associated with each half month bin assigned as the seasonal peak relative to latitude from North to South. Filled grey circles represent raw data points for peak date each season. Regression from linear modelling (dashed black line).
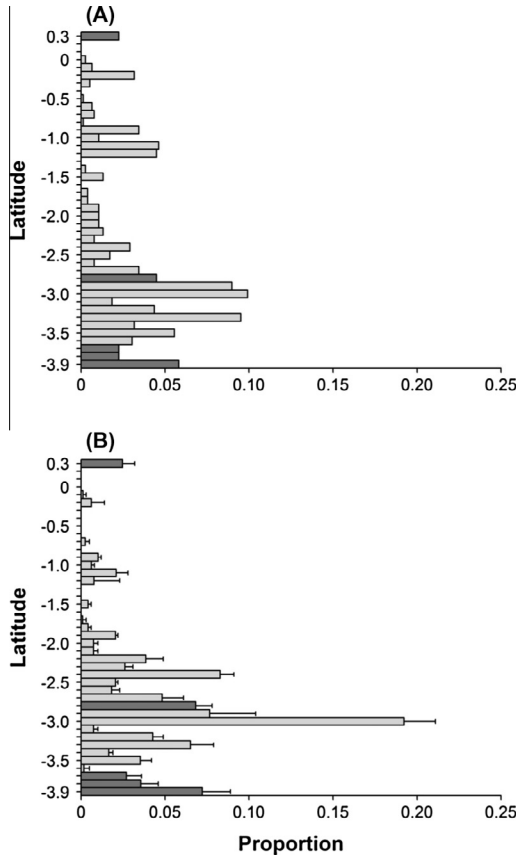
Fig. 4. Spatial patterns of nesting activity, relative to latitude: (A) proportion of olive ridley turtle nests observed along coastal transects (excluding non-nesting emergences); and (B) mean proportion of estimated nests (error bars indicate 95% confidence limits) when extrapolating total number of nests classified between ⩽1, 2 and 3 days old in each survey bin (see Fig. S4 for plots illustrating distribution of nesting activity for estimates based on the three age classes). Dark grey bars indicate latitudes where daily ground counts of nests are undertaken at the four monitoring locations (Pointe Denis, Gamba, Bame and Nyafessa).

ridley turtles are considered the most abundant of all sea turtles (Eguchi et al., 2007), yet globally there has been a net decline in olive ridley populations, such that they are currently listed as
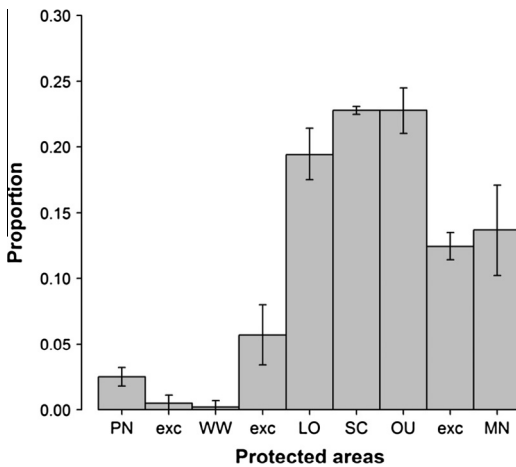

Fig. 5. Mean proportion of estimated olive ridley nests inside and between each of the National Parks and Reserves (i.e. protected areas) bordering Gabon's Atlantic coast (error bars indicate 95% confidence limits). Labels: Pongara National Park (PN), Wonga Wongue Presidential Reserve (WW), Loango National Park (LO), Sette Cama Reserve (SC), Ouangu Reserve (OU), Mayumba National Park (MN) and between protected areas (exc).

Vulnerable by the IUCN (Abreu-Grobois and Plotkin, 2008). However, despite several decades of research in the eastern Atlantic, and evidence that this species nests between Mauritania and Angola, including many of the region's islands (Fretey, 2001; Fretey et al., 2012; Mint-Hama et al., 2013; Varo-Cruz et al., 2011), knowledge on the status of the eastern Atlantic population remains incomplete, and so is considered Data Deficient (Abreu-Grobois and Plotkin, 2008; Conant et al., 2014; Pikesley et al., 2013b). Increasing the knowledge base for olive ridley turtles along the Atlantic coast of Africa is therefore a regional conservation priority (Formia et al., 2003; Mazaris et al., 2014). As such, we present below detailed data on the trends and status of the known nesting population in Gabon.

4.1. Olive ridley nesting effort

Previous research has largely focused on mass nesting assemblages of olive ridley sea turtles called *arribadas*, despite the fact that 'solitary' nesting, where turtles may nest independently of one another, occurs at numerous beaches worldwide (Dornfeld et al., 2015). Data from this study indicates that Gabon is an important rookery for solitary nesting olive ridley turtles, with the almost continuous presence of nesting activity spanning from Pongara National Park in the north to Mayumba National Park in
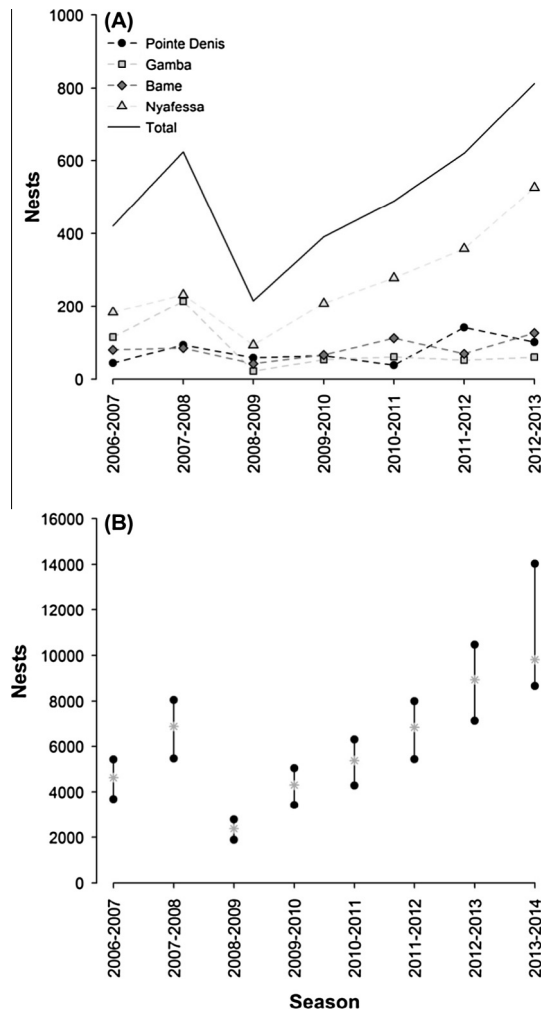
Fig. 6. Seasonal trends in: (A) number of nests at each of the four monitoring locations used in this study (based on modelled data corrected to include the beginning of the nesting season) and; (B) upper and lower (filled black circles) and median (asterisk) estimates of the number of olive ridley nests laid annually.

the south. Furthermore, in the absence of robust data over large spatial scales from other nesting aggregations in the region, the most recent estimates of nesting effort derived for 2013/2014 (8662–14,033 nests) suggest that Gabon hosts one of the most important rookeries for this species in the Atlantic (when compared to estimated nesting populations monitored at key nesting beaches elsewhere – Angola: 122 nests; Brazil: 2971 nests; French Guiana: 2600–3300 nests; Republic of Congo 497 nests; and Suriname: 411 nests annually (Abreu-Grobois and Plotkin, 2008; Godgenger et al., 2009; Plot et al., 2012; Weir et al., 2007)). However, deriving an index of female population size from estimates of nesting effort is complicated by resource availability at distant foraging grounds, as this likely drives plasticity in re-migration interval and clutch frequency (Broderick et al., 2003, 2001), which can strongly affect population estimates (Hays, 2000; Rivalan et al., 2006). Using the median range of estimates of the number of nests laid in Gabon over the seven seasons (range: 2370–9814) and an estimated clutch frequency of 1.8 and 2.5 nests per female (derived from non arribada populations; Abreu-Grobois and Plotkin, 2008; Miller, 1997), we estimated the number of nesting females per annum to be between 948 and 5452. Using a re-migration interval of 1.5 years (Miller, 1997) multiplied by the range of estimates of females nesting each season gives an estimate of between 1422 and 8178 breeding females, thus indicating it to be one of the largest documented breeding populations in the Atlantic (Abreu-Grobois and Plotkin, 2008). Furthermore, assuming that spatial patterns of nesting effort are consistent within and across seasons, analysis of seasonal trends based on the range of upper, lower, and median estimates for total nesting effort in Gabon over seven seasons suggests that this population is increasing with annual growth rates of between 14.0% and 19.8% (i.e. equivalent to a 2–3-fold increase) in nesting effort since 2006–2007.

4.2. Protected areas

Assessing the overlap between protected areas and core nesting regions to inform targeted conservation and/or monitoring efforts is important for effective conservation of sea turtles (Mazaris et al., 2014). Therefore, whilst the coastal survey revealed that Gabon's coastal network of protected areas encompassed a considerable proportion of nesting effort (approximately 81%); stretches of coastline outside of this network also received appreciable levels of nesting. This echoes similar findings for leatherback turtles in Gabon (Witt et al., 2009). However, in contrast to leatherback turtles, where nesting outside of protected areas is widely distributed, approximately 68% of all olive ridley nesting effort outside of protected areas was concentrated between Ouangu Reserve and Mayumba National Park along approximately 55 km (9%) of the surveyed coastline, an area that is not routinely monitored. Given that other solitary nesting populations in the Atlantic have shown strong nest site fidelity (Matos et al., 2012) further research is thus required to determine whether this location is important across seasons.

However, it is also worth noting that even though a considerable proportion of nesting occurs within protected areas, three of Gabon's six coastal protected areas are reserves and so are not likely to provide strict protection and enforcement that is associated with National Parks that have larger annual budgets. In addition, a range of illegal activities and external pressures continue to exist, even within their borders (Laurance et al., 2008; Pikesley et al., 2013a). For example, recent efforts to quantify the impact of commercial logging on leatherback turtles in Gabon (Pikesley et al., 2013a) have revealed that Sette Cama Reserve (an important nesting region for olive ridley turtles) hosts relatively high densities of beached logs that could potentially lead to mortality and

reduced nesting and/or hatching success (average density in 2011 was 18 ± 18.9 logs per 500 m CI: 15–21; $n = 152$). Additionally, 57% of strandings (defined here as turtles that washed ashore dead or alive) observed during the coastal transect were located inside National Parks and Reserves, with Sette Cama Reserve representing 46% of strandings inside protected areas (Fig. S5).

Bycatch in fisheries also remains a significant problem for sea turtles in Africa (Parnell et al., 2007; Weir et al., 2007), and so it is critical to note that, with the exception of Mayumba National Park which protects significant olive ridley marine habitat (Maxwell et al., 2011), the existing network of coastal protected areas only encompasses nesting beach habitats. By contrast, adult females and mating males spend several months of the nesting season in offshore areas where they mate and develop eggs, and as such, while the majority of nesting beach area is protected, the vast majority of inter-nesting habitat for olive ridley turtles remains unprotected; a similar situation occurs for leatherback turtles (Witt et al., 2008). Therefore, in order to adequately protect populations of sea turtles, further research is required to develop a more detailed understanding of at-sea habitat use (Pendoley et al., 2014). This would help facilitate more effective marine spatial planning efforts in support of MPA network design, the effective mitigation of oil and gas industry activities, and fisheries management in Gabon.

4.3. Monitoring techniques

This study represents the first national ground-based survey to cover extensive areas of Gabon's coast outside of monitored regions, highlighting that, in combination with ground-based monitoring data, traditional low-tech approaches are invaluable. However, estimating seasonal nesting effort and long-term trends from extensive ground-based coastal surveys requires an understanding of possible errors that may be introduced by the methodological treatment of the data.

In terms of data collected during the coastal survey and derived from the four monitoring locations, likely sources of error include: (1) Errors relating to nest ageing: Female nesting olive ridley turtles make recognisable tracks in the sand that are highly species-specific and are almost always focused along a narrow coastal strip, which is often subject to a range of environmental factors such as tidal patterns and exposure to wind and rain. The use of well-trained observers to maintain high levels of accuracy has thus been strongly recommended for beach based monitoring (Witherington et al., 2009), and so to minimise potential errors we used the same persons across the survey period to consistently age nests (authors: KM, PDA and DT), and included only nests considered ≤1, 2 and 3 days old in the subsequent analyses (i.e. those that displayed obvious signs of recent activity). In addition, the daily ground counts of nests recorded at the four monitoring locations were conducted at dawn and include only activity that is less than <1 day old. (2) Errors relating to spatial patterns of nesting: Scaling up population estimates from the coastal transect assumes that there has been little variation in spatial patterns of nesting within and across seasons and that just the relative densities of nesting effort have changed as indicated by trends at the four monitoring locations. This is plausible given that both solitary nesting populations of olive ridley sea turtles in the western Atlantic (Matos et al., 2012), and female satellite-tagged olive ridleys in Gabon have displayed strong nest site fidelity, with 8 of 13 turtles (62%) tagged in 2007/2008 and 2008/2009 re-nesting within 10 km of their previous nests (Maxwell et al., 2011). However, it is possible that the estimates of total nesting effort over the seven seasons could be prone to error given the extrapolation does not account for variability in habitat suitability, which has been shown to

influence the distribution of nesting effort even in areas with minimal tidal and/or wave activity (Katselidis et al., 2013). The approach presented here would therefore benefit from multiple surveys both within and across seasons to determine whether spatial or temporal variation in the distribution of nesting effort exists for this population (see Katselidis et al., 2013; Witt et al., 2009). (3) Errors relating to seasonal patterns of nesting effort (frequency distributions), which are central to scaling up survey data can significantly impact estimates of total nesting effort. Whilst several mathematical approaches have been devised to help construct seasonal curves using both incomplete and complete survey data (Girondot et al., 2006; Godgenger et al., 2009; Gratiot et al., 2006; Whiting et al., 2014), we felt that the approach demonstrated here ensured consistency in treatment of data across monitoring locations and more importantly is both transparent and repeatable across nesting seasons and aggregations. In particular, the shape of the seasonal curves derived from the reconstruction of nest beach monitoring data corresponds closely to that modelled for olive ridleys in neighbouring Republic of Congo (Godgenger et al., 2009) and so is likely an accurate reflection of seasonal patterns of nesting effort. However, the addition of data from forthcoming seasons that address current data gaps at the beginning of the nesting season will help refine these estimates.

5. Conclusions

Current population assessments of olive ridley turtles are often based on census data with inadequate spatial and temporal coverage. However, for some populations such as in the eastern Atlantic there is a significant lack of data that has resulted in them being excluded from the latest *IUCN Red List* status assessments altogether (Abreu-Grobois and Plotkin, 2008; Mazaris et al., 2014). This extensive ground-based coastal survey therefore provides important information on both spatial patterns of nesting and population trends along the coast of Gabon. In particular, this study suggests that Gabon hosts one of the most important olive ridley rookeries in the Atlantic, if we consider the available data to date. Additionally, this study complements the existing knowledge base and further emphasises the regional and global importance of Gabon's nesting sea turtle populations (Maxwell et al., 2011; Witt et al., 2011, 2009, 2008). Gabon is therefore better placed in terms of available data than most African countries to support the design and management of an extensive MPA network that adequately represents and protects large marine species such as sea turtles. However, given that many parts of the African coast still have not been sufficiently assessed or surveyed, data on known nesting grounds in neighbouring Republic of Congo (Bal et al., 2007; Godgenger et al., 2009), Angola (Weir et al., 2007) and other African nations bordering the Atlantic coast (Fretey, 2001) need to be integrated before we can design effective protected area networks and/or generate robust assessments to detect regional changes in the status of olive ridley sea turtles in the eastern Atlantic.

Acknowledgements

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2015.05.008.

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