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Green turtle population recovery at Aldabra Atoll continues after 50 yr of protection

Adam M. Pritchard[1,*], Cheryl L. Sanchez[2,3], Nancy Bunbury[2,1], April J. Burt[2,4], Jock C. Currie[2,5,6], Naomi Doak[2], Frauke Fleischer-Dogley[2], Kristian Metcalfe[1], Jeanne A. Mortimer[2,7], Heather Richards[2], Janske van de Crommenacker[2], Brendan J. Godley[1]

[1]Centre for Ecology and Conservation, College of Life and Environmental Sciences, University of Exeter, Cornwall TR10 9FE, UK
[2]Seychelles Islands Foundation, La Ciotat Building, Mont Fleuri, Victoria, PO Box 853, Seychelles
[3]Department of Biology, University of Pisa, Via A. Volta 6, 56126 Pisa, Italy
[4]Department of Plant Sciences, Oxford University, South Parks Road, OX1 3RB, UK
[5]South African National Biodiversity Institute, Kirstenbosch Botanical Gardens, Claremont, Cape Town, Western Cape 7735, South Africa
[6]Institute for Coastal and Marine Research, Nelson Mandela University, Gqeberha, 6031, South Africa
[7]Department of Biology, University of Florida, Gainesville, Florida 32611, USA

ABSTRACT: Green turtles *Chelonia mydas* have been subject to high levels of anthropogenic exploitation, with harvesting at their nesting sites especially pronounced throughout the late 19th and early 20th centuries, leading to worldwide declines. Due to their delayed sexual maturity, long-term protection and monitoring is crucial to allow and accurately demonstrate population recovery. Subsequent to their exploitation, Aldabra Atoll (Republic of Seychelles) has offered the longest continuous protection for nesting green turtles anywhere in the Western Indian Ocean, beginning in 1968. Here, we document the continuing recovery of that population by estimating clutch production within 12 mo nesting seasons over 50 yr of monitoring. An estimated mean of 15 297 clutches were laid annually between December 2014 and November 2019. This represents an increase of 173 % since Aldabra's intensive monitoring programme was initiated in 1980, and 410–665 % since 1968. Clutch number increases were recorded at all but 1 of 6 monitored beach groups around the atoll but were most pronounced at Settlement Beach, where exploitation of nesting females was historically most intense. Seasonality data since 2000 showed a year-round nesting season, with elevated activity in April–June peaking on average in May, and a potential shift to later in the year over time. This study highlights the considerable contribution of Aldabra Atoll to regional green turtle numbers and the benefit of long-term protection and monitoring at what can be considered a global reference site for this species.

KEY WORDS: *Chelonia mydas* · Marine turtle · Population assessment · Seasonality · Track counts · Western Indian Ocean

1. INTRODUCTION

Large, migratory marine species are among the world's most threatened vertebrates, frequently due to a range of anthropogenic impacts and the difficulties associated with protecting them across their extensive ranges (Lascelles et al. 2014). Inconsistent monitoring effort across such large spatial scales, and the logistical and financial difficulties presented by monitoring at sea, challenge population assessments and can result in IUCN Red List classifications of Data Deficient (Davidson et al. 2012). Monitoring of colonial

*Corresponding author: amp221@exeter.ac.uk

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breeding and/or feeding grounds, be they at sea for whales (Dulau et al. 2017) and sharks (Taylor 1996) or on land for seabirds (Wooller et al. 1992), sea turtles (Seminoff & Shanker 2008) and pinnipeds (Condit et al. 2007), is often the most effective way of assessing population status. Whilst this may bias data towards certain life history stages and complicate extinction risk assessments at global scales (Broderick et al. 2006), it can also focus conservation and management efforts by identifying key sites to target for protection and allow conservation success to be measured.

Green turtles *Chelonia mydas* provide a case study of site-targeted conservation resulting in a profound impact on an endangered migratory marine vertebrate. Despite considerable anthropogenic exploitation resulting in massive historical reductions (McClenachan et al. 2006), successes of long-term conservation programmes have been documented at major rookeries in Australia (Chaloupka & Limpus 2001), Costa Rica (Troëng & Rankin 2005), Ascension Island (Weber et al. 2014), Hawaii (Balazs & Chaloupka 2004) and the Baja Peninsula, Mexico (Seminoff et al. 2015). The Western Indian Ocean is home to many green turtle rookeries, including 4 IUCN Marine Turtle Specialist Group assessment sites (Seminoff 2004). Several studies have revealed positive responses to protection at selected regional nesting sites (Bourjea et al. 2007, Lauret-Stepler et al. 2007, Chaloupka et al. 2008, Mortimer et al. 2011), but none have covered a period as long as the present study, given that data collection was initiated at Aldabra Atoll almost 15 yr earlier than any other site in the region (Mortimer 1985, 1988, Mortimer et al. 2006, 2011).

Aldabra Atoll, in the southern Seychelles (Thomson & Walton 1972), was first discovered by Arabian sailors in 916 AD (Stoddart 1971). Turtle exploitation at Aldabra began in 1770 but became commercialised with the first established settlement in 1888, resulting in stark population decline by the mid-20th century and a subsequent total ban on the capture of green turtles in 1968 (Frazier 1974, Stoddart 1984). Aided by geographic isolation and numerous protective area designations beginning in 1976, and including inscription as a UNESCO World Heritage site in 1982 (UNESCO 2019), green turtles have remained largely undisturbed at Aldabra since its initial protection.

Turtle track count surveys on Aldabra began in the late 1960s, with annual reproductive effort as low as 2000–3000 clutches season^{-1} (Hirth & Carr 1970, Frazier 1976, Gibson 1979). In 1980, track count methodology was standardised and a substantial increase in the nesting green turtle population was documented up to 2008 (Mortimer et al. 2011). This estimate (which assumed 3–5 clutches female^{-1}), placed Aldabra's population at 3100–5225 nesting females annually, making it the second largest nesting site in the Western Indian Ocean region after Europa Atoll in the French Iles Eparses (Le Gall 1988, Mortimer et al. 2011, 2020).

Mortimer et al. (2011) observed nesting increases across the atoll's 6 beach groups, with 2 primary groups (West Grande Terre and Settlement Beach; see Fig. 1) contrasting in their respective importance in recent decades. Between 1996 and 2008, the historically more exploited Settlement Beach (Mortimer et al. 2011) observed an increase in nesting 3 times faster (113%) than the more densely nested West Grande Terre beaches (34%) (Mortimer et al. 2011). Considering this pattern, a better understanding of shifts in relative levels of nesting across the atoll over time is needed to inform management.

Using track count data, we investigated how Aldabra's green turtles have responded to 50 yr of sustained protection (1968–2019). With the benefit of adding 11 yr of data, we assessed the relative contributions of different beach groups to the atoll-wide population nesting over time and investigated whether Settlement Beach has sustained its pronounced growth. Nesting seasonality on Settlement Beach was also re-assessed, with near-daily recent data used to identify the nesting peak and whether this has shifted over time. Finally, we reviewed the regional importance of Aldabra's green turtle population and make recommendations for further research to ensure Aldabra continues to act as a global reference site for this species.

2. MATERIALS AND METHODS

2.1. Study site

Aldabra Atoll, in the Western Indian Ocean (9° 25′ S, 46° 20′ E), is one of the most remote islands of the Seychelles. At ca. 34 × 14.5 km, with a land area of 155 km^2 surrounding a 226 km^2 lagoon, it is one of the world's largest raised coral atolls. The atoll has 68 turtle nesting beaches: 52 around the outer perimeter and 16 on the inner coastline within the lagoon. To facilitate reporting efforts, the outer beaches are assigned to one of 6 groups across 4 islands (see Fig. 1). The beaches fringing the lagoon, primarily visited by small numbers of nesting hawksbill turtles *Eretmochelys imbricata* and rarely used by green turtles, were excluded from this study.

2.2. Data collection and processing

This study used track count surveys (Schroeder & Murphy 1999) during 1980–2019 to assess the size and status of Aldabra's nesting green turtle population, with researchers recording all tracks produced by nesting females over the previous 24 h on each site visit. For details of historical data collection, see Text S1 and Table S1 in the Supplement at www.int-res.com/articles/suppl/n047p205_supp.pdf and Mortimer et al. (2011).

Under a standardised monitoring protocol introduced in 1980, tracks were separated into 3 clearly distinct categories. In the first category, digging was recorded ('tracks with digging'; TD). Two other categories of tracks showed no evidence of digging, either when the female did not dig because her emergence was stopped by an obstacle such as a log or cliff erosion ('emergence stopped by obstacle'; ESBO) forcing her to return to the sea, or when there was no evidence of digging or disturbance ('half-moon'; HM). To estimate total nesting effort, the number of TD tracks was scaled via interpolation of recorded values between surveys. As discovered by Mortimer (1988, 1990), characteristics such as sand texture and moisture content vary across Aldabra's beach groups and impact the proportion of successful nesting attempts (henceforth 'nesting success'). To account for this variation and that of sampling effort (Text S1, Table S1), numbers for each beach group were interpolated separately, and the proportion of TD tracks which resulted in clutch deposition was calculated using nesting success ratios unique to each beach group (Mortimer 1988). The northern beaches were also split into 2 interpolation groups, as different nesting success ratios were found for their eastern and western beaches (Mortimer 1988). Nest estimates per beach group per season, as well as their percentage contributions, are presented in full in Table S2. For more information on how the calculation of clutch estimates differed from Mortimer et al. (2011), see Text S2.

2.3. Statistical analysis

Number of clutches laid within and across Aldabra's beach groups were modelled as a function of season (with Aldabra's 12 mo nesting season from December–November), with a generalised additive model (GAM), using the 'gamm' function from the 'mgcv' package (Wood 2017). To account for temporal autocorrelation, we investigated models with and without auto-regression (AR) correlation structures, including AR(1) and AR(2) processes. The AR(1) structure was chosen based on examination of autocorrelation plots of model residuals and Akaike information criterion (AIC) scores. When using 'gamm' to investigate potentially non-linear temporal trends, a thin-plate spline was fitted to the year term, for which the number of knots was automatically determined using generalised cross validation by setting $k = -1$; the gamma parameter was fixed at 1.4 to reduce over-fitting (Wood 2017).

Percentage contributions of the beach groups to the atoll-wide total were calculated. With these data, a GAM was constructed in the same fashion as above, but this time the nesting group contribution to the total (%) was modelled as a function of nesting season (1–365 d, n = 38).

To investigate seasonality, we used data from January 2000 to December 2019 (when the most complete track count data were available; Text S2). A GAM was constructed with number of clutches modelled as a function of nesting season, but this time a cubic cyclic spline (fit to 12 mo) was fit to loop the model to the annual cycle.

The R package 'phenology' (version 7.3; Girondot et al. 2006) was used to investigate seasonality further, to identify if there had been a potential recent shift in seasonal nesting peaks on Settlement Beach (2000–2001 to 2018–2019). This methodology, assuming a sinusoidal structure, is described in full in Girondot et al. (2006) and has been applied in the Republic of the Congo (Godgenger et al. 2009), but is described here in brief in Text S3.

For all analyses, if a GAM model supported a linear relationship, a generalised linear model (GLM) was subsequently conducted to assess the strength of the relationship. All analyses are provided to a 95% confidence interval and were conducted using R version 3.6.1 with RStudio (R Core Team 2021, RStudio Team 2020). IUCN methodology (Seminoff 2004) was applied to estimate population growth rates, with comparisons made between the clutch averages of 5 full nesting seasons to account for inter-season variation.

3. RESULTS

3.1. Monitoring data

Between January 2000 and December 2019, 30 828 track count surveys were undertaken across the 52 studied nesting beaches (Fig. 1; Table S1). The most consistently surveyed beach groups were, in order: Settlement Beach (mean ± SD: 278.8 ± 0.0 surveys

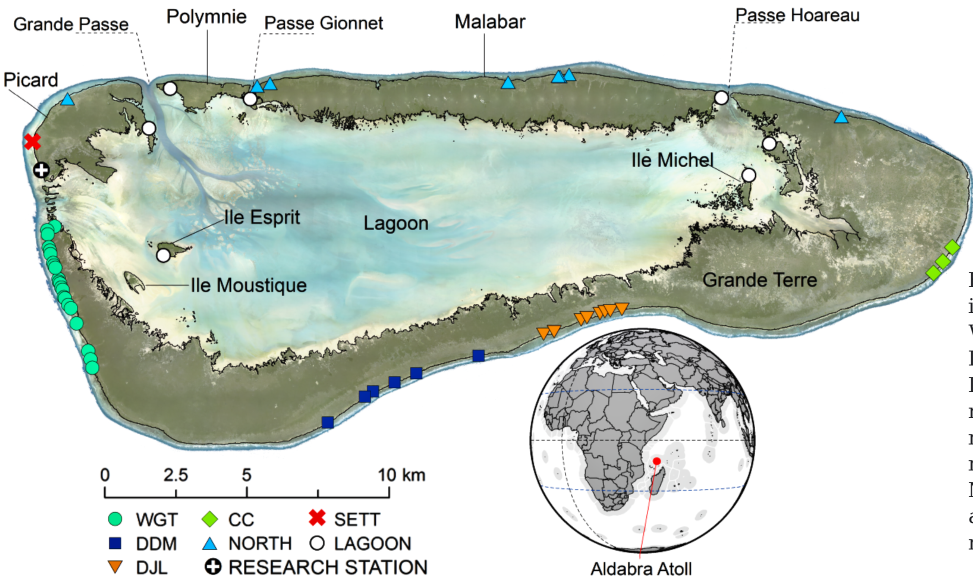

Fig. 1. Aldabra Atoll, highlighting the major beach groups. WGT: West Grande Terre; DDM: Dune d'Messe; DJL: Dune Jean-Louis; CC: Cinq Cases; North: northern beaches; SETT: Settlement Beach. The areas of the 4 main islands of Grande Terre, Malabar, Picard and Polymnie are 111.1, 25.9, 9.4 and 1.9 km^2, respectively (Seychelles Islands Foundation unpubl. data)

yr^{-1}), West Grande Terre (37.4 ± 3.0), North (18.5 ± 0.7), Dune Jean-Louis (12.6 ± 1.2), Cinq Cases (11.7 ± 0.5) and Dune d'Messe (11.6 ± 1.3). During these surveys, 112 107 individual tracks were categorised. Of these tracks, 86.6% were classified as TD, 9.1% as ESBO and 4.2% as HM. TDs were used to estimate the number of clutches annually and thus derive nesting population estimates. Of the 14 017 surveys undertaken from December 1980 to December 1999, 16 603 tracks were categorised, of which 91.4% were classed as TD, 5.2% as ESBO and 3.3% as HM.

3.2. Nesting clutch size estimates and population growth

In applying IUCN methodology (Seminoff 2004) to calculate population growth and using a comparison of the annual clutch average of the last 5 nesting seasons surveyed to the first 5 seasons of reliable data, the estimated annual number of clutches rose from a 5 season (1980–1981 to 1984–1985) average of 5606 to an estimate of 15 297 (2014–2015 to 2018–2019; Fig. 2, Table S2). This represents a 173% increase in the number of clutches at an overall growth rate of 2.6% yr^{-1}, estimated to be linear by the GAM (approximate significance of the smooth term: F = 63.0, estimated degrees of freedom [edf] = 1, p < 0.001). The estimated number of clutches increased by an average of 288.6 ± 36.9 season^{-1} ($F_{1,37}$ = 61.3, p < 0.001, adjusted R^2 = 0.6). If the same 3–5 clutch-to-turtle ratios from Mortimer et al. (2011) are applied, the mean annual estimate of 15 297 clutches equates to an estimated seasonal nesting average of 3059–5099 turtles nesting on Aldabra.

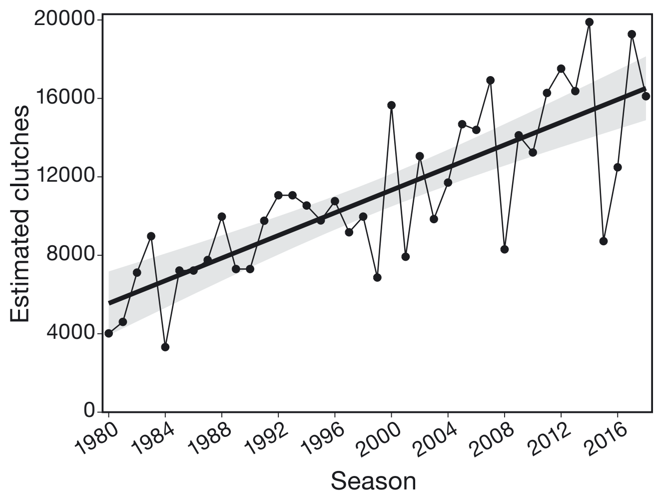

Fig. 2. Estimated clutches of green turtles per season on Aldabra Atoll (1980–2019; 39 seasons). Year refers to the first calendar year of the season (e.g. 1980 = Dec 1980–Nov 1981). Estimated clutches taken from Table S2. A generalised additive model was used to detect a linear relationship; grey ribbons: approximate 0.95 confidence intervals

Using a comparison of the annual clutch average of the last 5 nesting seasons surveyed (15 297 from December 2014 to November 2019) to the earliest recorded estimates (2000–3000 clutches around 1968; Frazier 1976, Gibson 1979), our study reveals a nesting clutch increase of 410–665% over the 50 yr of Aldabra's protection.

3.3. Key beach group trends

Separated into beach groups, the West Grande Terre beaches were found to host the most nesting attempts, as found by Mortimer et al. (2011). West Grande Terre's proportional contribution to Aldabra's nesting attempts varied from a minimum of 30.0% in 1980–1981 to a maximum of 83.2% in 1983–1984 but showed no clear trend during the monitoring period (Fig. S1). The overall increase in nesting attempts on West Grande Terre reflected an increase in clutches across Aldabra; however, the rate of increase at this beach group was considerably slower than that at Settlement Beach. Clutch estimates for West Grande Terre rose from an average of 3603 (1980–1981 to 1984–1985) to 7847 (2014–2015 to 2018–2019), an increase of 117.8% with an annual growth rate of 2.0%. The GAM estimated an increasing linear slope (F = 31.6, edf = 1, $p < 0.001$), and a linear model supported this relationship (number of clutches increased by 146.1 ± 26.5 season^{-1}; $F_{1,37}$ = 30.7, $p <$ 0.001, adjusted R^2 = 0.4; Fig. S1). Over the same period, an increase on Settlement Beach from 264–3618 clutches was also observed (Fig. 3); this represented a total increase of 1271.2%, with a growth rate of 6.9% — another significant increase (GAM: F = 108.8, edf = 2.9, $p < 0.001$, adjusted R^2 = 0.9). This resulted in the percentage contribution of Settlement Beach to the atoll's overall nesting attempts increasing significantly from an average of 5.6% (1980–1981 to 1984–1985) to 24.6% (2013–2014 to 2017–2018; GAM: F = 68.0, edf = 2.9, $p < 0.001$, adjusted R^2 = 0.8; Fig. 3b). The periods of significant change at Settlement Beach identified on the GAM models were found to begin in 1990 for clutch numbers and 1988 for the beach's percentage contribution (Fig. 3).

3.4. Seasonality

Nesting attempt analysis from January 2000 to December 2019 showed a year-round nesting season, with elevated activity in April–June peaking on average in May (Fig. 4a). There was no shift in peak nesting dates at Settlement Beach from seasons 2000–2001 to 2018–2019 (GAM: F = 2.5, edf = 1, p = 0.13, adjusted R^2 = 0.7; Fig. 4b). However, although the p-value was >0.05 (likely due to high variability, especially in 2017), we did find an increasing trend towards later peak nesting dates.

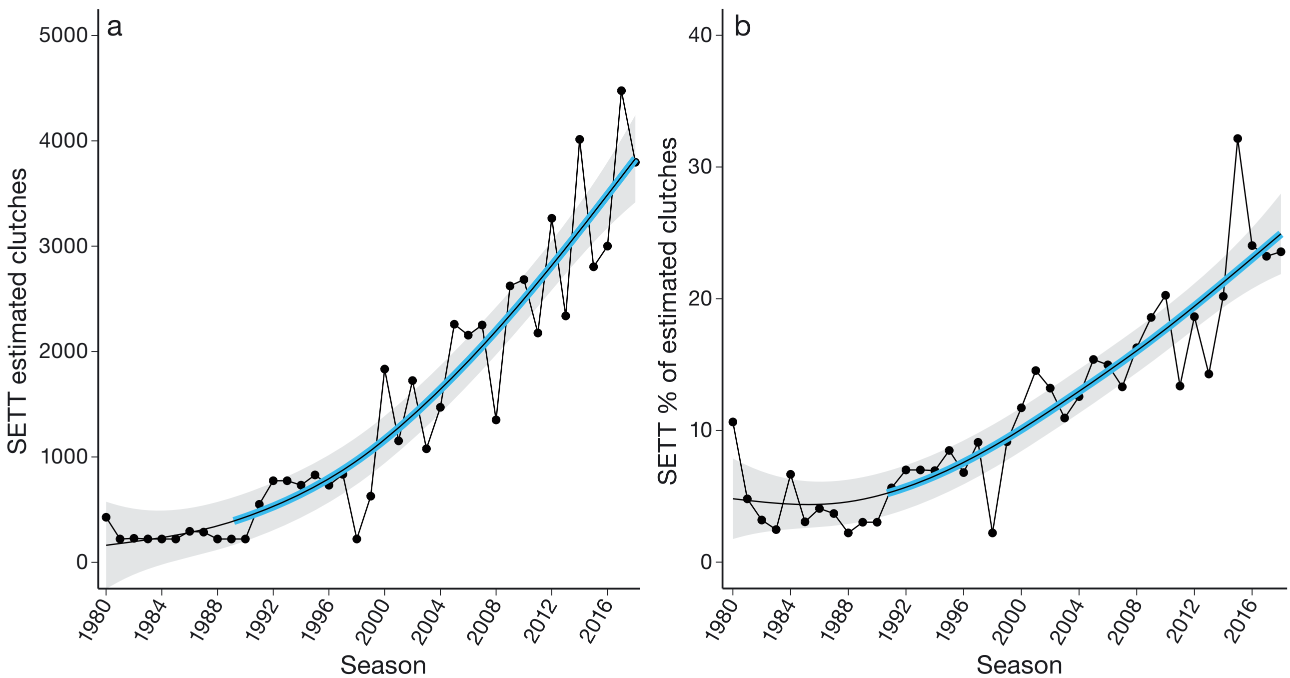

Fig. 3. Total estimated clutches at (a) Settlement Beach (SETT) and (b) relative nesting contribution of Settlement Beach to Aldabra Atoll (1980–2019; 39 seasons). Year refers to the first calendar year of the season (e.g. 1980 = Dec 1980–Nov 1981). Estimated clutches and relative contribution both taken from Table S2. Generalised additive models were used to detect relationships; grey ribbons: approximate 0.95 confidence intervals; blue: periods of significant change

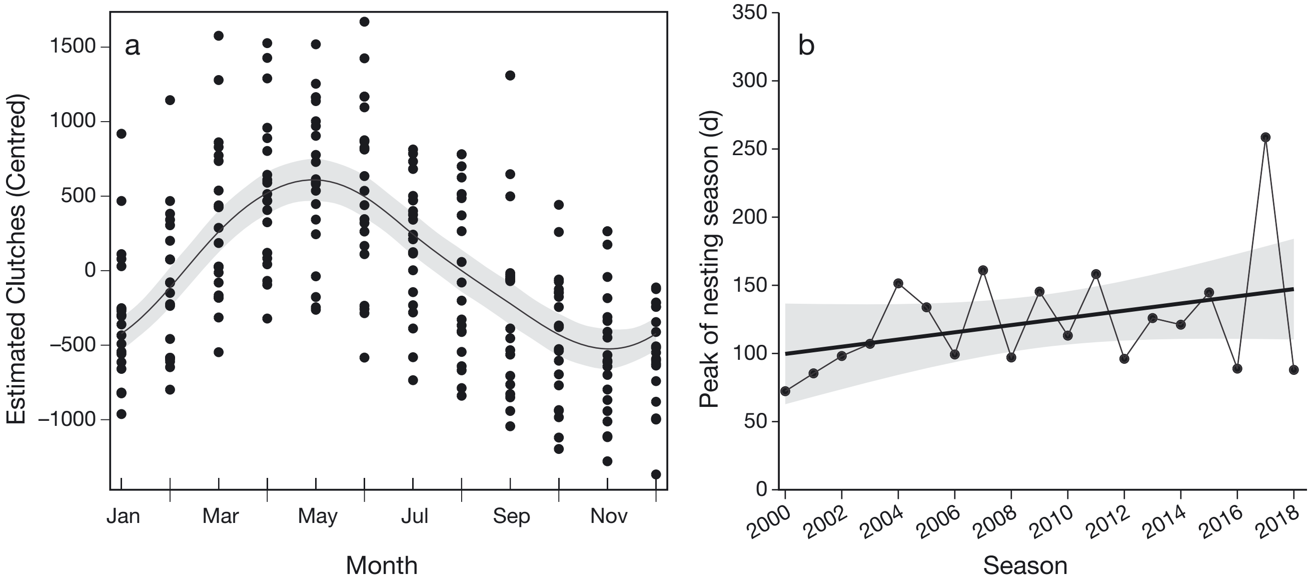

Fig. 4. Seasonality of nesting green turtles at Aldabra Atoll. (a) Estimated clutches per month across the atoll, centred about the mean and based on data from Jan 2000 to Dec 2019. Grey ribbons: approximate 0.95 confidence intervals around a generalised additive model-generated cyclic smoothing spline. (b) Phenology of the nesting peak on Settlement Beach (SETT) from 2000 to 2018. Year refers to first year of the season (e.g. 2000 = Dec 2000–Nov 2001)

4. DISCUSSION

Long-term monitoring of marine turtle populations is essential to assess the effectiveness of various conservation measures including cessation of harvest, low levels of disturbance on the island and stricter protection in many range states in the Indian Ocean. We analysed 39 yr of standardised track count data on Aldabra (1980–2019), and our comparison with early nesting estimates reinforces the regional importance of the atoll's nesting green turtle population and shows that its recovery still continues, 50 yr after its protection in 1968. The increase in nesting attempts is concordant with previous research (Mortimer et al. 2011), with the historically heavily exploited Settlement Beach continuing its greater rate of recovery. Although Aldabra supports year-round nesting, our results show clear nesting seasonality and suggest that the peak of nesting attempts may be shifting later.

4.1. Monitoring methodology and reliability

Despite the advantages and popularity of track count surveys (Schroeder & Murphy 1999), there are important caveats to consider when assessing their reliability and accuracy in generating population trajectories for sites with multiple beaches (Godley et al. 2001). The success of nesting attempts can vary widely across beaches, with females often making more frequent nesting attempts on some beaches (Mortimer 1990). Seasonality may bias data if monitoring is not performed year-round or at least over the peak of the nesting season (Jackson et al. 2008). Remigration intervals, typically lasting 2–5 yr, can also bias studies, owing to their propensity to vary widely due to environmental conditions (Broderick et al. 2001). Our study made efforts to account for these potential biases: different nesting conditions across beach groups were addressed by individual interpolation and the use of nesting success ratios unique to each beach group (Mortimer 1988); consistent year-round monitoring for nearly 40 yr helped describe seasonal fluctuations and reduce the noise of inter-annual variability. We suggest, therefore, that the estimates presented here provide a reliable index of how female reproductive effort on Aldabra has changed.

4.2. Aldabra's nesting population and growth trend

Although historical track count data on Aldabra are sparse (Frazier 1971), estimated turtle numbers at the turn of the 20th century are placed at 6000–8000 based on a combination of historical data and trade statistics (Mortimer 1985). This would indicate that Aldabra's nesting population, while increasing, has far from recovered to pre-exploitation levels. Density-mediating factors for Aldabra's population in the future might include seagrass and algal availability at foraging sites (Lal et al. 2010), rising sea levels reducing available beach area (conservative sea level rise is estimated to reduce the area of the atoll by around 25% by 2100; Gerlach 2008) and increasing intensity of storms and cyclones (Malan et al. 2013). These predictions are largely speculative, and the specific impacts of climate change on nesting turtle populations require further study (see review by Patrício et al. 2021).

4.3. Key beach group trends

The rapid rise in overall nesting contribution on Settlement Beach — historically the most heavily exploited site — was predicted by Mortimer et al. (2011), who noted that the beach accounted for 36% of available beach length but only 12% of nesting attempts. A similar pattern of greatest increases in nesting attempts in areas most accessible to human settlement (and therefore most heavily harvested prior to protection) has also been recorded on Ascension Island (Weber et al. 2014). The increasing trend at Settlement Beach shows no signs of slowing and is likely to continue in coming years. Other beach groups, such as West Grande Terre, may have stabilised or even declined in their relative contribution to Aldabra's nesting in recent years (Fig. S1).

4.4. Seasonality

Nesting seasonality in the Western Indian Ocean region is highly variable, even on Aldabra itself, where nesting on West Grande Terre was found to peak approximately 2 mo later than at Settlement Beach (Mortimer 2012). Drawing atoll-wide conclusions from peak nesting dates at Settlement Beach alone is therefore problematic. Nonetheless, the clearly observed year-round nesting found across the atoll is common for green turtles in the Western Indian Ocean, and our observed nesting season with an Austral winter peak is consistent with previous work on Aldabra (Mortimer 2012) and other notable rookeries in the region (D'Arros Island, Amirantes Group, Seychelles: Mortimer 2011; Diego Garcia, Chagos Archipelago: Mortimer et al. 2020; Grande Glorieuse: Lauret-Stepler et al. 2007; Mayotte: Bourjea et al. 2007; and Moheli: Bourjea et al. 2015b). Other Western Indian Ocean turtle rookeries also experience Austral summer peaks (Tromelin and Europa: Lauret-Stepler et al. 2007; Juan de Nova: Lauret-Stepler et al. 2010). When investigating seasonality in the region, Dalleau et al. (2012) and Mortimer (2012) did not recognise genetics as a factor, citing sea surface temperatures or other feeding ground characteristics as more likely determinants.

4.5. Aldabra's nesting population within a regional context

Placing Aldabra's population within a regional context must be treated with caution due to the lack of standardisation in track count methodologies across sites, and indeed the lack of consensus, even within geographic regions, about the numbers of clutches per female (Schroeder & Murphy 1999, Bourjea et al. 2007, Esteban et al. 2017). Additionally, areas such as Madagascar and Africa's east coast have few long-term population studies, despite hosting important turtle foraging and nesting sites (Metcalf et al. 2007, van de Geer et al. 2022). Nonetheless, our study has updated Mortimer et al.'s (2011) 5 yr estimate (2003–2004 to 2007–2008) of 15 669 clutches to 15 297 clutches (2014–2015 to 2018–2019), maintaining Aldabra's status as the second largest (monitored) breeding site within the wider Western Indian Ocean region — comparable to Moheli in the Comoros (12 000–18 000 clutches; Bourjea et al. 2015a,b) but likely lower than Europa in the French Iles Eparses (8750–30 363 clutches; Le Gall et al. 1986, Le Gall 1988, Lauret-Stepler et al. 2007) (Table S3). Despite the age and lack of precision of Europa's estimate, with an approximate increase in track counts of 3% yr^{-1} between 1983–1984 and 2005–2006, the breeding population remains substantial (Lauret-Stepler et al. 2007) (Fig. 5, Table S3). Further north, the Chagos Archipelago comprises 5 atolls which together produce an estimated 20 500 clutches annually (with an increasing trend) (Mortimer et al. 2020), with an estimated seasonal mean of 6 clutches $female^{-1}$ (Esteban et al. 2017).

4.6. Moving forward

With few published studies around the Western Indian Ocean reporting such long-term monitoring (only Europa, Grande Glorieuse and Tromelin have

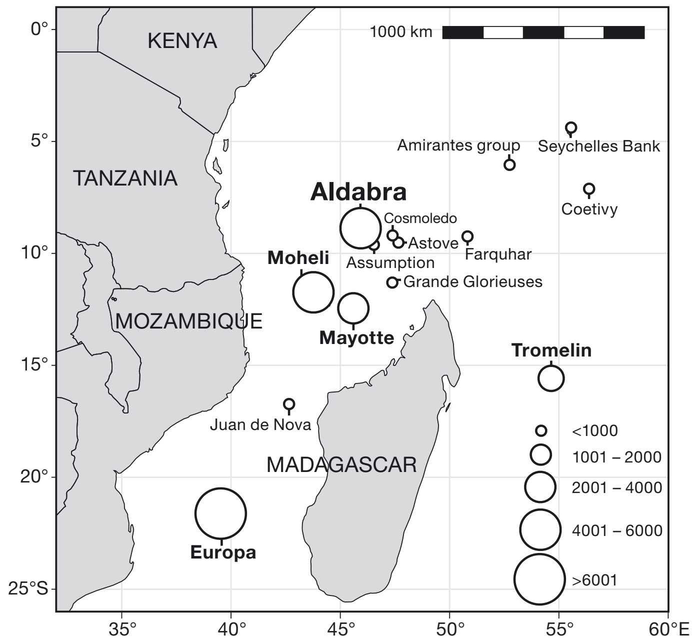

Fig. 5. Status of major Western Indian Ocean (WIO) nesting populations of green turtles. The largest green turtle nesting populations in the WIO are indicated in bold. Key indicates average number of females nesting annually: the largest sites are described in Table S3; Grande Glorieuses described in Lauret-Stepler et al. (2007); other sites described in Mortimer (1984), Mortimer (2011) and Mortimer et al. (2011). For further information see Table S3. Not pictured, but contributing to the stock of green turtles in this region, is the Chagos Archipelago in the Central Indian Ocean. The green turtle population there is substantial, with a recent annual clutch estimate of 20 500 (Mortimer et al. 2020)

been the focus of consistent surveying for 20 yr or more; Lauret-Stepler et al. 2007), the importance of ongoing work on Aldabra, the longest continually protected and monitored population of nesting green turtles in the Western Indian Ocean, is heightened. Notwithstanding, some revisions to the monitoring programme are recommended to improve the quality and value of the data.

We recommend that each beach group be monitored at least monthly, as some 3 mo gaps highlighted in Text S1 (n = 31 since 2000) could allow seasonal shifts to go unnoticed. An updated study of nesting success would support future population estimates, as nesting success ratios were last estimated in 1988 (Mortimer 1988). Since those estimates were made there has been a concerning build-up of marine debris on the southern beaches (Burt et al. 2020), potentially contributing to the atoll-wide percentage increase of ESBOs from 5.2 % pre-2000 to 9.1 % post-2000. Beach profiles, through factors such as erosion and debris build-up, may also have changed nesting success rates (Burt et al. 2020).

Detailed spatial data collected on turtle tracks, nesting beach fidelity and remigration studies from tagging data would improve understanding of how Aldabra's turtles are using the beaches in space and time, and explore further seasonality differences across the atoll. We also recommend work to obtain estimates of number of clutches per female per season specific to Aldabra so that nesting population trends can be estimated with greater certainty. These would be most easily obtained by satellite tracking or remotely downloaded GPS loggers (Bourjea et al. 2007, Weber et al. 2014, Esteban et al. 2017).

Given Aldabra's importance as a regional reference site for nesting turtles, research into understanding current and future sex ratios under climate change scenarios is of high priority and should include beach modelling (beach erosion) under future sea level rise scenarios to assess the vulnerability of nesting beaches (Varela et al. 2019).

Aldabra's case study joins a growing body of literature illustrating that green turtles are responsive to harvesting bans on their nesting beaches, both regionally and globally (Chaloupka & Limpus 2001, Balazs & Chaloupka 2004, Troëng & Rankin 2005, Weber et al. 2014, Seminoff et al. 2015). While other threats such as beach erosion and temperature rise certainly exist, the potential ecological and socioeconomic impacts of rapidly rising turtle populations, not just in the Western Indian Ocean, but globally, offer exciting research avenues. Healthy green turtle populations can maintain low algal cover on reefs (Wabnitz et al. 2010), and their grazing pressure on seagrass meadows can increase leaf nitrogen levels and nutritional content (Moran & Bjorndal 2005). On the other hand, rebounding populations of turtles may risk overgrazing of already degraded seagrass meadows, potentially causing declines in both fish numbers and fisher tolerance of turtles (Arthur et al. 2013, Heithaus et al. 2014, Gangal et al. 2021).

Key factors also unknown on Aldabra are the dispersion of adults and juveniles from the population — information which would allow insights into key regions where these turtles may play an important ecological role and, indeed, may be in need of active conservation efforts. These knowledge gaps could be filled through a combination of satellite tracking (Jeffers & Godley 2016), population genetics (Jensen et al. 2018) and modelling of hatchling dispersal (Scott et al. 2017).

4.7. Conclusions

This study documented the continued recovery and regional importance of Aldabra's nesting population of green turtles. Further recommendations, both to strengthen the monitoring protocol on Aldabra and fill research gaps, have been identified. Aldabra serves as a key example of the benefits of long-term protection that may be applicable to other depleted turtle populations around the Western Indian Ocean and beyond. This study, carried out at a logistically challenging site, presents a replicable methodology, which can demonstrably inform the status and phenology of nesting populations in a region generally lacking in long-term data.

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