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The value of satellite tracking across multiple year cohorts to identify key areas for conservation

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While satellite tracking is widely used to identify areas of conservation importance, whether there is a need to continue tag deployments across many years is unclear. We show that destinations of migrating animals from the same breeding population can differ significantly across years, and hence we highlight the value of multi-year tracking studies. Between 2012 and 2024, we used Fastloc-GPS Argos and Iridium tags to track 58 green turtles (*Chelonia mydas*) from their nesting sites in the Chagos Archipelago. If tracking had taken place in a single year, the number of countries used as foraging destinations could have been hugely underestimated (n = 1 country in 2024 versus n = 7 countries across years). Overall, 47% of tracked individuals foraged in the Seychelles, which likely hosts hundreds of thousands of foraging turtles across age classes. Further, the importance of foraging in areas beyond national jurisdiction (ABNJs) was only revealed by tracking over multiple years. Across years, 9% of tracked individuals foraged on the Saya de Malha Bank, a remote ABNJ, equating to likely >1000 adult females and >10 000 green turtles using this foraging area. This cumulative insight from multi-year tracking likely applies broadly to capital breeders where there is environmental variability across the foraging range.

1. Introduction

Current rates of biodiversity loss are scientifically recognized as the world's sixth mass extinction [1], triggered by a range of separate and synergistic anthropogenic drivers including overexploitation, habitat loss and degradation, the spread of invasive species and climate change. Conservation interventions have shown that success is possible in countering the decimation and rebuilding natural ecosystems [2]. Many multilateral commitments have been set up with the aim of preventing further biodiversity loss, such as the '30 × 30 worldwide initiative', resolving to protect and restore 30% of the world's land and seas by 2030 and secure a 90% reduction in extinction rates by 2050, agreed by 190 nations at the UN Biodiversity Conference COP15 in 2022 [3]. Further, the more recently signed United Nations High Seas Treaty highlights how preserving and rebuilding ocean biodiversity needs informed protection not only inside the exclusive economic zones (EEZs) of each country but also in areas beyond national jurisdiction (ABNJs) [4]. Indeed, ABNJs are one of the last frontiers of exploitation [5] and pose a challenge for the management of protected species that have large ranges or migrate across large distances.

Central to these initiatives that span the globe is the need to objectively identify key areas for conservation [6,7]. For marine megafauna, satellite tracking has been widely used to identify key areas for a range of species, including fish, marine mammals, seabirds and turtles [8,9]. However, pervading across these studies is the question of how much satellite tracking is needed to identify key areas for conservation, as tracking is expensive and can have ethical issues [10]. Often, tracking studies are conducted in 1 year, and in many cases, it may be unclear whether there are benefits to equipping animals across multiple years. For sea turtles, three studies have shown inter-annual variability in adult movement patterns [11–13], although the generality of this finding is unknown. To address this knowledge gap, here we describe the tracking results from equipping nesting green turtles across multiple years. We made deployments in a region, the Western Indian Ocean (WIO), where the conservation landscape is particularly dynamic with changes in sovereignty underway that will impact what was formerly one of the world's largest conservation zones, the Chagos Archipelago Marine Protected Area (MPA) [14]. In this way, we assess the value of multi-year tracking studies in understanding species movements and driving conservation planning.

2. Methods

(a) Turtle tracking

Satellite transmitters were attached to post-nesting green turtles on Diego Garcia (7.42º S, 72.45º E), using quick-setting epoxy (see [15] for full details). Turtles were equipped during 2012 (n = 8), 2015 (n = 10), 2017 (n = 5), 2018 (n = 12), 2022 (n = 10), 2023 (n = 10) and 2024 (n = 8), across the months of June to October (first four tracking years published in [16]). Argos-linked Fastloc-GPS tags were used from Sirtrack (model F4G 291A; Sirtrack, Havelock North, New Zealand; n = 4, 2012) and Wildlife Computers (models SPLASH10-BF, SPLASH10-F-296A and SCOUT-NAV; Wildlife Computers, Seattle, Washington; n = 57, 2012–2024), as well as a small sample of Iridium-linked tags from Telonics (Sea Trkr-4370-4; Telonics Inc., Mesa, Arizona; n = 2, 2023).

(b) Track analysis

Satellite data were filtered to remove locations with less than four satellite fixes and those inferring travel speeds >5 km h^{-1}. Argos-relayed Fastloc-GPS locations were kept where residual error values were <35, and Iridium-relayed locations were kept where Quick Fix Pseudoranging (QFP) was resolved. For one of the Argos-linked tags, no Fastloc-GPS locations were received for the duration of transmission. In this case, Argos tracking locations of classes 3, 2 and 1 were used instead.

Tracks were processed and visualized in QGIS and R [17] using the spatial features package 'sf' [18]. Turtles were considered to have arrived at a foraging ground when tracks switched from long-range, directed movement patterns to remaining localized with sharp turning angles (clear from visual inspection of the tracks). Arrival locations were considered representative of each foraging site as they did not differ from the centroid of foraging locations at relevant map scales. Migratory bearings were calculated as if in a straight line between departure and arrival sites, using the R package 'geosphere' [19], and were tested for differences among years using a randomized Mardia–Watson–Wheeler test [20] in the R package 'circular' [21].

3. Results

Of 63 green turtles from the Chagos Archipelago that were equipped with satellite transmitters, 58 were tracked to foraging grounds where they remained resident for weeks or months of further transmission at sites across the WIO (figure 1*a,b*).

There was notable variability in foraging destinations across years (figure 1*c–e*; electronic supplementary material, figure S1). Despite a reasonably stable sampling effort, the number of countries that individuals were tracked to varied from as low as one in some years (2024, n = 8 tracks) up to six in other years (2022, n = 8). There were significant inter-annual differences in the compass heading distributions across all tracking years (Wg_{12} = 24.43, $p < 0.05$) with, for example, the spread of directional headings being as low as 18º in one year (2024) and as high as 94º and 112º in other years (2012, also n = 8, and 2022, respectively). For example, across all years, 56% of turtles travelled to foraging sites within the EEZ of the Republic of Seychelles and on the Saya de Malha Bank which is jointly managed by Seychelles and Mauritius. In 2024, eight of eight turtles travelled to this area. The probability of this occurring purely by chance was extremely low, being 0.56^8 or $p < 0.01$, i.e. there is likely a biological driver for the variability in foraging destinations across years.

Across years, almost half were tracked to sites within the Seychelles (47%, n = 27), and a quarter to Africa and Madagascar (24%, n = 14). Smaller proportions remained within the Chagos MPA (16%, n = 9), went to the Saya de Malha Bank ABNJ on the Mascarene Plateau (9%, n = 5) or went north to the Maldives (5%, n = 3). Overall, 81% of equipped turtles crossed into international waters in transit to their foraging destinations (n = 47).

4. Discussion

Our results show that inter-annual variability in foraging destinations likely applies broadly across sea turtle species, having now been reported in green turtles (this study), leatherbacks [11] and loggerheads [12,13]. Inter-annual variability in movement patterns has also been reported in other marine megafauna, including marine mammals, fish and birds [22–24]. For sea turtles,

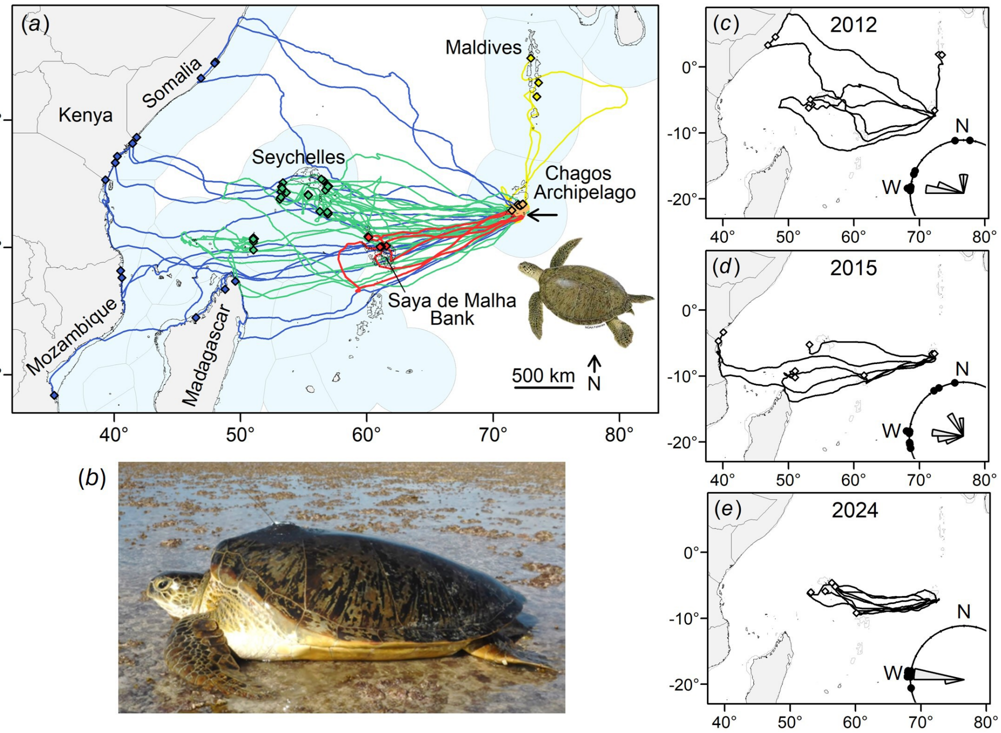

Figure 1. (*a*) Green turtles breeding in the Chagos Archipelago return to foraging sites across the Western Indian Ocean (green: Seychelles, 47%; blue: Africa and Madagascar, 24%; orange: Chagos MPA, 16%; red: Saya de Malha Bank (area beyond national jurisdiction), 9%; yellow: Maldives, 5%; $n = 58$, 2012–2024). Exclusive economic zones (EEZs) shown in pale blue; 100 m depth contour shown in black. The horizontal arrow indicates the deployment site in the Chagos Archipelago. (*b*) Equipped green turtle before departure. Destinations were variable across years, as seen in three example years shown here: (*c*) 2012, $n = 8$, (*d*) 2015, $n = 9$ and (*e*) 2024, $n = 8$. See electronic supplementary material, figure S1, for all tracking years. Inset circular plots show migratory bearings calculated as the straight line between departure and arrival sites. The NNW points in (d) represent individuals that travelled to the Great Chagos Bank which is close (<100 km) to the tagging location and so not clearly evident at the scale of the map.

when considering how much satellite tracking is needed to identify key conservation areas, one suggestion is that the optimal number of years to sample might be a function of the variability in remigration intervals (RIs) seen in a breeding population, so that if most animals return to breed after 3, 4 or 5 years, tracking for at least 5 years would be necessary to capture all foraging cohorts. If RIs are typically 2 or 3 years, tracking across 3 years may be sufficient. Equally, the ideal number of animals to track per year should be a function of the variability between individuals, so that if there is great variability in foraging destinations seen in the first year of tracking, then a larger number of tracks per year may be needed. Finally, animals should ideally be equipped throughout the breeding season; future studies might usefully assess if individuals nesting outside of the peak season exploit different foraging grounds, as has been shown for leatherback turtles in some nesting areas [25]. The reasons for inter-annual variability in movement patterns may vary across taxa. Climate warming is expected to drive shifts in species' geographical ranges. These range shifts underlie long-term and inter-annual changes in the movement patterns of tiger sharks (*Galeocerdo cuvier*) in the North Atlantic, for example [24]. Similarly, shifting wind regimes and glacier retraction have caused altered foraging behaviour and space-use patterns in birds and mammals in the Arctic [22,23]. For green turtles in the Mediterranean, shifting foraging area dynamics have caused a change in migratory movement patterns over time [26]. However, other factors likely drive the inter-annual variability in migration destinations for sea turtles more broadly. Female sea turtles typically breed every 2–5 years [27], and each individual generally maintains fidelity to a particular foraging site throughout its adult life [28]. So the individuals tracked in a particular year will be different to those tracked in the following year, for example. For each individual, the decision on whether to breed or not in a particular year is likely driven by the attainment of a specific level of body condition (i.e. threshold fat reserves) to sustain a breeding migration [29]. So, if foraging conditions differ across the range of a population, then individuals in one part of the range might attain sufficient body condition to initiate a breeding migration, while those elsewhere might not. In this way, the destinations of migrating individuals tracked after breeding will vary from one year to another. Under this scenario, in some years, the individuals that nest may come from a restricted part of the overall range of a population, likely explaining why all the turtles we tracked in 2024 travelled to broadly the same region.

It is noteworthy that we recorded a huge range of migration distances, from a few tens of kilometres to sites on the Great Chagos Bank, to migrations of over 5000 km to mainland Africa. A large range in migration distances has also been shown for green turtles nesting in the Galápagos Islands, with some staying resident and others travelling 1500 km to Central America [30]. This breadth of migration distances and foraging sites is thought to reflect the experience of individuals when they are drifting on ocean currents in the early part of their lives, with individuals selecting foraging sites as adults that they encountered earlier in their lives [31,32].

Across a wide range of migration distances, our tracking results highlight the importance of submerged banks and ABNJs in addition to coastal waters for foraging green turtles, with half of the tracked turtles residing on submerged banks, for example.

Using the proportionality information from our tracking results and based on an estimated 20500 green turtle clutches laid annually in the Chagos Archipelago [33], assuming an average clutch frequency of five and RI of 4 years, we can predict the approximate numbers of adult female green turtles foraging in each region that nest in the Chagos Archipelago. Based on these reproductive parameters, we estimate that of the green turtles nesting in the Chagos Archipelago, there are around 8000 foraging in the Seychelles, 4000 foraging in Africa and Madagascar, 2500 foraging on submerged banks within the Chagos Archipelago, 1500 on the Saya de Malha Bank and 800 in the Maldives. As breeding adults make up <2% of the benthic foraging population [34], across size classes there are likely in the order of hundreds of thousands of green turtles foraging in the Seychelles and tens of thousands in the ABNJ of the Saya de Malha Bank, for example.

Taken together, our results and those from different taxa clearly indicate the broad conservation significance of submerged banks. The shortest migrations we recorded were to the Great Chagos Bank, the world's largest atoll [35], which is also a key foraging site for the hawksbill turtles (*Eretmochelys imbricata*) that nest in the Chagos Archipelago [36]. Hawksbill turtles tend to feed mainly on sponges and other benthic invertebrates [37], while green turtles in the WIO feed mainly on seagrasses [38,39]. The co-occurrence of hawksbills and green turtles in broadly the same area points to a variety of benthic habitats, and hence high conservation importance of the Great Chagos Bank. Highlighting the conservation importance of this bank is particularly important given the recent agreement on the change to the sovereignty of the Chagos Archipelago and hence the likely introduction of new conservation designations for the region and the removal of the existing large-scale MPA [40]. This importance of submerged banks for green turtles was reiterated by the destinations of many other tracked turtles. For example, we tracked 9% of turtles to the Saya de Malha Bank. This bank has no emergent land, making it a globally unique mid-ocean shallow sea, its bathymetry interacting with oceanic currents to create upwelling and increased productivity [41]. The waters above the Saya de Malha Bank are officially high seas waters, although there is a Joint Management Agreement in place between the Seychelles and Mauritius to manage the seabed [42]. In addition to being important for green turtles, the bank is said to support a diverse reef-fish community, and the adjacent deep waters contain a high diversity of pelagic fish and cetaceans [41,43]. Because of this rich biodiversity, the bank has been classified as an ecologically or biologically significant area. The joint management of this ABNJ might serve as an exemplar for the management of high seas areas, although an intensive trawl fishery from Thailand is thought to have damaged seabed ecosystems and reduced fish and shark abundance dramatically between 2015 and 2020 and continues at a reduced level [44]. Further, vessels from other distant-water fishing nations are also known to target the bank [41,44].

While we tracked green turtles foraging widely through the WIO, it is noteworthy that sea turtles are afforded protected status under the Indian Ocean-South-East Asian (IOSEA) Marine Turtle Memorandum of Understanding while inside the EEZs of every country of the region, apart from Somalia [45]. While IOSEA represents one of the most significant multinational instruments to conserve sea turtles and their habitats, such efforts can still lack effectiveness due to limited implementation [46]. Nevertheless, a key conclusion from our work is that such international agreements are of great importance given the wide-ranging trans-border movement of individuals, and we highlight the conservation importance of high-use sea turtle areas in ABNJs as well as within the EEZs of nations. Future studies might usefully assess if individuals nesting at different times of the year exploit different foraging grounds, as has been shown for leatherback turtles in some nesting areas [25].

Ethics. The research was approved by Swansea University and Deakin University Ethics Committees and the British Indian Ocean Territory (BIOT) Administration of the UK Foreign, Commonwealth and Development Office and complied with all relevant local and national legislation. The study was endorsed through research permits (0002SE12, 0007SE15, 0002SE17 and 0009SE18, 0001SE22, 0007SE23, 0007SE24) from the Commissioner for BIOT. Until constitutional change transferring Chagos Island sovereignty from the UK to Mauritius is completed (as per the treaty signed in 2025), all scientific study permits are required to be issued by the UK overseas territory administration.

Data accessibility. All data are available from the Dryad Digital Repository [47].

Supplementary material is available online [48].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. K.L.S.: data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; N.E.: funding acquisition, investigation, methodology, writing—review and editing; J.A.M.: investigation, writing—review and editing; A.R.: data curation, formal analysis, writing—review and editing; G.C.H.: conceptualization, funding acquisition, investigation, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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