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Occurrence of leatherback turtles around Australia

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ABSTRACT: Leatherback turtles *Dermochelys coriacea* are a pelagic species, globally endangered due to multiple anthropogenic impacts. Although protected under Australian legislation, species-specific practical protection has been hampered by sparse information about leatherback distribution in Australian waters. To fill this gap, we obtained records of leatherback interactions with fisheries gear, opportunistic sightings at sea, beach stranding events and non-target capture in shark control programs. We evaluated the temporal and geographic distribution of records and assessed potential bias in observation opportunity based on human population density and fishery activity. Based on 1073 leatherback observations from 1990 to 2022, we found that sightings were unevenly distributed right around Australia, encompassing longitudes from 105.4° E to 165.1° E and latitudes from 43.7° S to 10° S. In the extreme southeast of Australia, hotspots were apparent during December to March (austral summer). In temperate and subtropical latitudes to the west and east of Australia, hotspots appeared predominantly during June, July and August (austral winter), but were also apparent, albeit weaker, to the east in all other months. Our results confirm that the species is present around Australia in all months of the year and has a much wider geographic and offshore distribution around Australia than previously reported. Hence, we inferred that Australian waters are highly important for migrating and foraging leatherbacks from subpopulations breeding in the Pacific and Indian Oceans, all of which are at high risk of extinction, and we suggest that Australian management agencies have crucial roles in protecting these endangered animals.

KEY WORDS: Marine turtles · Sea turtles · Endangered species · Spatial distribution · *Dermochelys coriacea* · Fishery interactions

1. INTRODUCTION

The leatherback turtle *Dermochelys coriacea* is the largest of the world's 7 species of marine turtles and the only living representative of the taxonomic family Dermochelyidae. Globally, leatherback populations have declined steeply due to degradation of their nesting habitat, excessive harvest for human consumption, inadequate regulatory mechanisms, fisheries bycatch, ingestion of and entanglement with plastic and other marine debris, climate change and sea level change (see National Marine Fisheries Service & U.S. Fish and Wildlife Service 2020 and references therein).

Leatherbacks very rarely nest on Australian shores (Limpus 2009) and there is no evidence of a distinct Australian-nesting subpopulation. However, migrating and foraging leatherbacks do occur around Australia, although only sparse data are available (Robins 1995, Limpus 2009, Benson et al. 2011). Although genetic studies are incomplete, the likely sources of leatherbacks migrating and foraging in Australian waters are the Critically Endangered West Pacific Ocean subpopulation and the Data Deficient Northeast Indian Ocean subpopulation (Wallace et al. 2013). In a recent status review, both subpopulations have been evaluated as at high risk of extinction (National Marine Fisheries Service & U.S. Fish and

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Wildlife Service 2020) and thus warrant urgent conservation attention across their range.

Legislative protection is extended to leatherbacks under Australia's Environment Protection and Biodiversity Conservation Act 1999 (Australian Government 2021) and a variety of state-based legislation, as well as fisheries- and maritime-specific legislation, similar to other marine turtle species. However, development of species-specific practical protection has been hampered by sparse information about leatherback distribution in Australian waters (Department of the Environment and Energy 2017). Our study contributes towards filling that gap.

We wanted to assess leatherback occurrence around Australia as widely as possible, with a focus on observations recorded in recent decades. The recency of data was deemed important to maximise the relevance for diminished leatherback subpopulations now in urgent need of more effective conservation measures. In contrast, prior studies predominantly relied on older observations and/or were geographically limited to southeastern Australia (Limpus & McLachlan 1979, observations up until 1979; Bone 1998, observations from 1889 to 1998; Limpus 2009, observations available prior to August 2004; Hays et al. 2023, observations from 1862 to 2022).

We aimed to (1) accumulate reports of leatherback interactions with fisheries gear, opportunistic sightings at sea, beach stranding events and non-target capture in shark control programs, (2) evaluate the temporal and geographic distribution of leatherback reports and (3) evaluate potential bias in observation opportunity. Due to data limitations (see Section 2), we could not evaluate anthropogenic threats.

2. METHODS

To obtain formal records of chance encounters with leatherbacks, we submitted requests to government agencies responsible for environmental and fisheries management and to public engagement programs. *A priori* we were obliged to accept conditions stipulated by various organisations regarding availability, confidentiality and re-distribution of original datasets. Ultimately, we also accepted that some data requests would not be granted. All data providers are listed in the Acknowledgements section. Although some records were supported by photographs, we could not check the validity of each record and therefore we relied on the data quality standards of each organisation, noting also that leatherback turtles are readily distinguishable from hard-shelled marine turtles (family Chelonidae) by their flexible, leathery carapace and very large size (Limpus 2009). The majority of records did not include turtle dimensions, sex and health status, and the majority of fishery records did not indicate fishery gear type.

We adopted 1990 as our starting date so that our study period would approximately match the 30 yr generation length estimated for leatherback turtles (Wallace et al. 2013). We merged records from all sources, after we had standardised date and location formats. As required by data sharing agreements, we removed personal details (if present) and retained only date, location and species fields for each record. For cases with incomplete dates, the day and month were interpolated from observation comments where available. Similarly, apparent errors in geographic coordinates were corrected where possible, by reference to place names in observation comments. Some fishery records used a geographic grid system (e.g. QFish Logbook Grid, see https://qfish.fisheries.qld.gov.au/Help). For each of these records, a point location (latitude/longitude) was randomly selected within the designated grid square. We discarded apparent duplicate records and records with date or location anomalies that could not be resolved. While the remaining records represented unique observation events, we accepted that some individual leatherbacks could have been observed on more than 1 occasion.

Records were categorised as 'coastal' and 'offshore', respectively within and beyond 80 km from the coast. This distance accorded with the availability of relevant physical data for offshore waters. We matched offshore records with fine-scale temperature and bathymetry data using (1) global foundation sea surface temperature at 0.05° × 0.05° horizontal resolution (Good et al. 2020) provided by Copernicus Marine Service (https://doi.org/10.48670/moi-00168) and (2) 0.0025° × 0.0025° horizontal resolution bathymetry data 2009 from Commonwealth of Australia (Geoscience Australia) (http://dx.doi.org/10.4225/25/53D99B6581B9A). For analysis and mapping, we used R Statistical Software v.4.2.2 (R Core Team 2022) and QGIS v.3.22 (QGIS.org 2021).

Considering that each leatherback record depended on opportunistic visual observation by a person, we evaluated the availability of potential observers as follows. We used chi-squared goodness-of-fit tests to determine (1) whether coastal records were distributed in similar proportions to human population density around the Australian coast and (2) whether records within commercial fishing areas were distributed in similar proportions to the relative intensity of fishery activity. For (1), we used Australian Bureau of Statistics human population estimates 2001 to 2021, Australian Bureau of Statistics Population estimates by Local Government Area, 2001 to 2022 (https://www.abs.gov.au/statistics/people/population/regional-population/latest-release; accessed 6 March 2023). For (2), we derived an index for relative fishery activity based on the Australian Bureau of Agricultural and Resource Economics and Sciences Fishery Status Reports (https://doi.org/10.25814/qvv9-da24) for the years 2010 to 2020. While this was not an exact match to the data for fishery interactions used in our analysis, it was the most relevant representation of fishery effort we could obtain.

3. RESULTS

We compiled a total of 1073 records of leatherback turtle observations that collectively encompassed longitudes from 105.4° E to 165.1° E and latitudes from 43.7° S to 10° S and spanned the years 1990 to 2022. In aggregation, these records showed that leatherback turtles were observed all around Australia, from coastal shallows to pelagic waters with depths >5000 m. The estimated sea surface temperatures for offshore records ranged from 12.7 to 31.2°C (Fig. 1).

Annual totals showed an overall increase from 15 leatherback records in 1990 to 94 records in 2018, but the temporal trend was notably uneven (Fig. 2). Monthly totals of coastal records fluctuated irregularly over the entire period, while offshore records initially increased (2000 to 2003), with subsequent

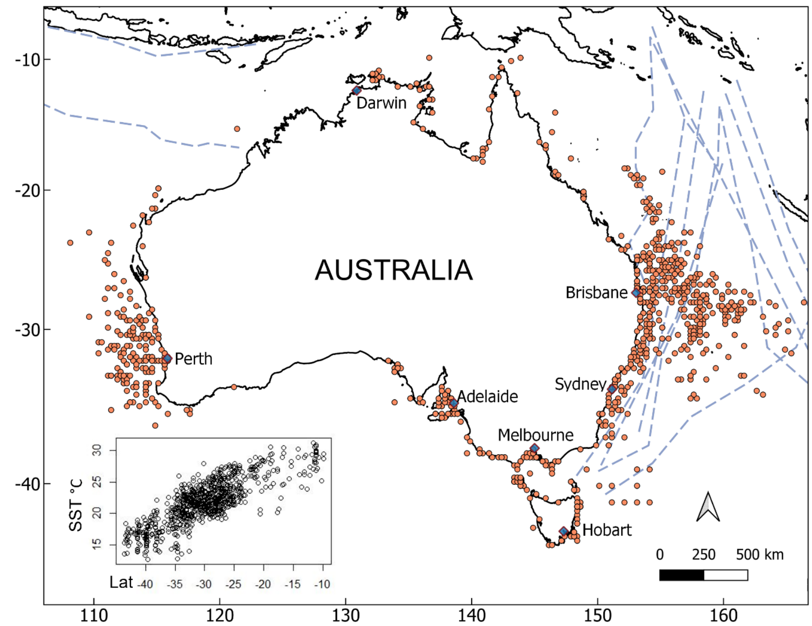

Fig. 1. *Dermochelys coriacea* observations (red dots) around Australia, 1990 to 2022. Inset lower left: estimated sea surface temperatures (SST) for the location and date of each observation. Dashed lines: simplified trajectories of satellite-tracked leatherback females moving towards Australian waters from regional nesting sites (Benson et al. 2011, Swaminathan et al. 2019)

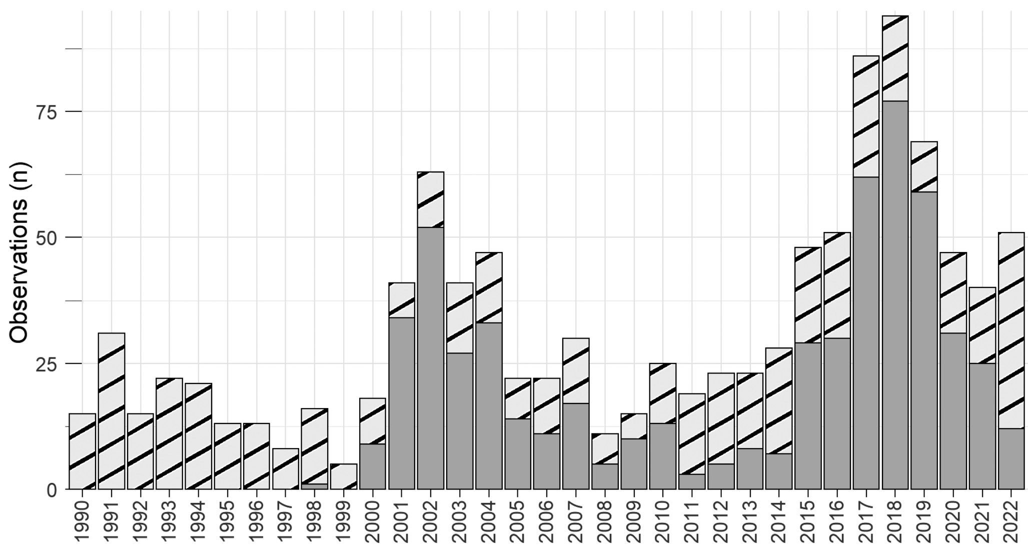

Fig. 2. *Dermochelys coriacea* observations were unevenly spread over the years 1990 to 2022, both for coastal observations (⩽80 km from shore, bars with diagonal lines) and offshore observations (>80 km from shore, solid grey bars). See Section 4 regarding disparate start and end dates for contributed datasets in this compilation, and regarding potential influence of electronic monitoring in fisheries

decline, then showed a steeper increase from about 2015 (Fig. 3).

The geographic distribution of observations showed localised hotspots in irregular patterns. In the extreme southeast of Australia, hotspots were apparent during December to March (austral summer), whereas in temperate and subtropical latitudes to the west and east of Australia, hotspots appeared predominantly during June, July and August (austral winter) but were also apparent, albeit weaker, to the east in all other months (Fig. 4).

Coastal records comprised disproportionately more observations near densely populated coastal areas and disproportionately few observations near sparsely populated coastal areas. There was a statistically significant difference in spatial distribution from what would be expected based on human population density (χ^2 = 1541.9, df = 2, p < 0.001).

Across commercial fishing areas, there was a disproportionately large number of leatherback records in areas of moderate and high fishing activity and disproportionately few records in areas with low fishing activity. There was a statistically significant difference from what would be expected based on our index of fishing activity (χ^2 = 499.06, df = 2, p < 0.001).

4. DISCUSSION

Our findings confirm that leatherback turtles occur in Australian waters during all months of the year, with greater abundance and a broader geographic distribution around Australia than previously reported (Limpus & McLachlan 1979, Limpus 2009, Hays et al. 2023).

4.1. Temporal trends in leatherback observations

Leatherback observations showed an irregular increasing trend broadly consistent with expanding effort in data collection. Importantly, the increase in observations during the past 3 decades cannot be ascribed to leatherback population growth. The latter would be implausible, given that regional leatherback populations have suffered steep historic and ongoing declines (Tapilatu et al. 2013, Wallace et al. 2013, Martin et al. 2020, National Marine Fisheries Service & U.S. Fish and Wildlife Service 2020) and nesting occurrences in Australia (Limpus 2009) are far too low to support the number of turtles sighted offshore.

Comprehensive trend analysis was precluded by disparate timespans of contributed data subsets. Data

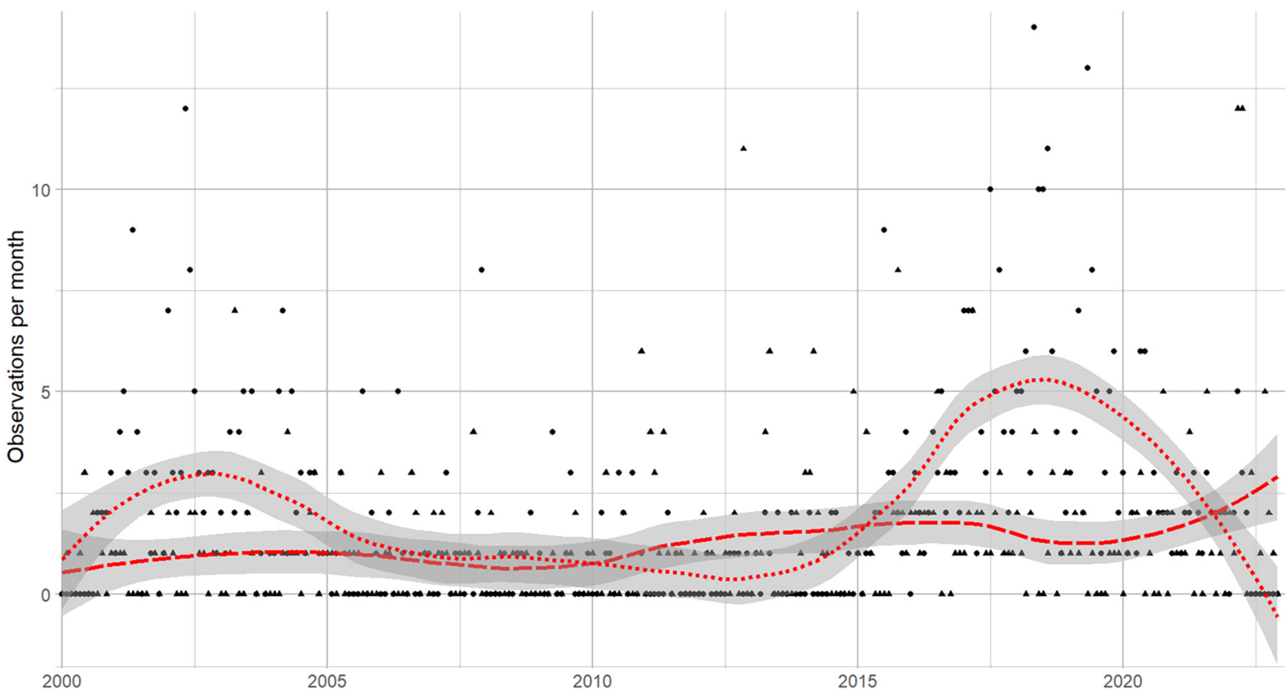

Fig. 3. *Dermochelys coriacea* observations from 2000 to 2022 showing monthly frequency for coastal observations (⩽80 km from shore, filled triangles) and offshore observations (>80 km from shore, filled circles). Loess smoothers were added to visualise trends (dashed red line: coastal observations; dotted red line: offshore observations; and grey shaded areas: 0.95 confidence bands)

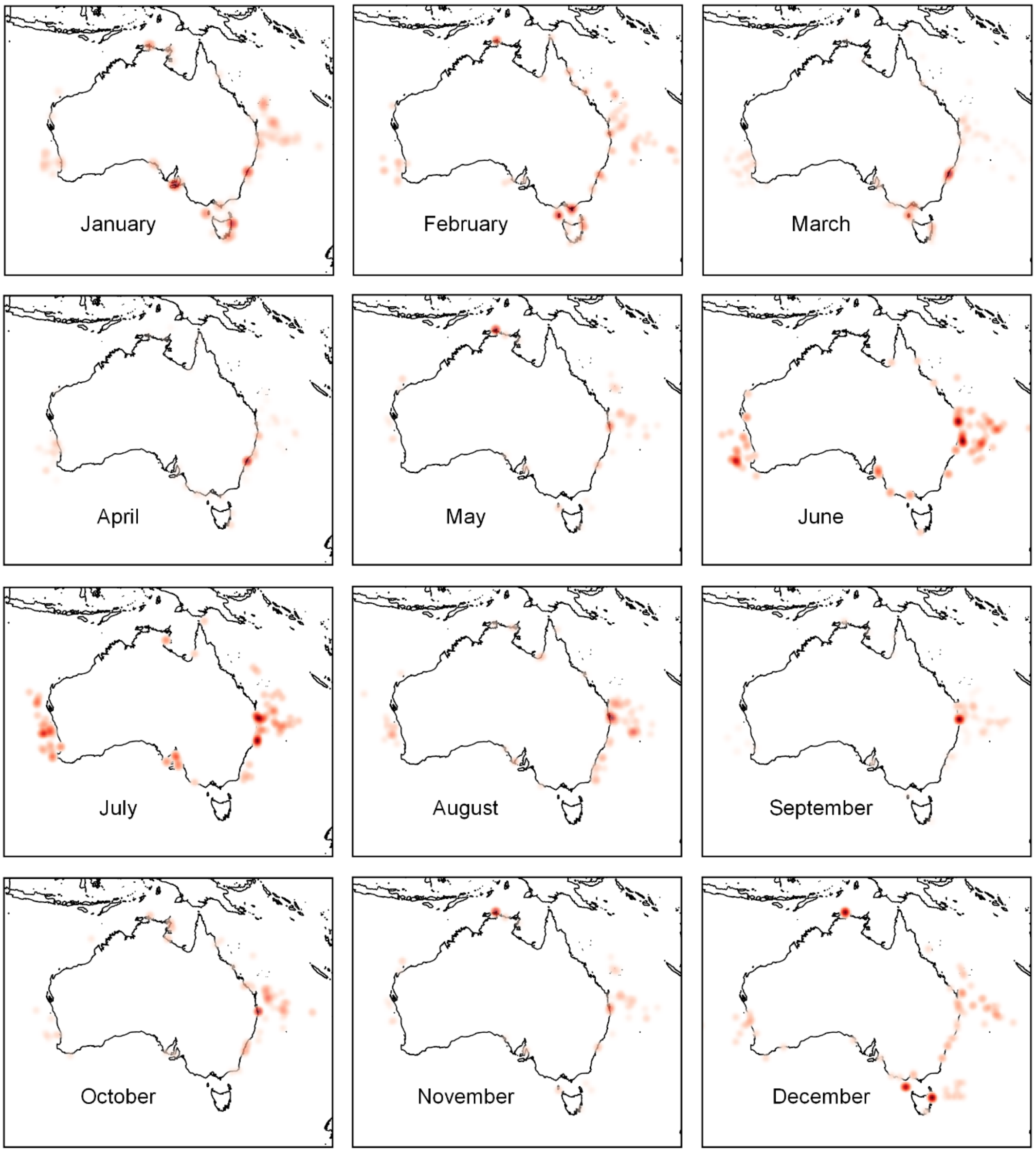

Fig. 4. *Dermochelys coriacea* observations (1990 to 2022) with heatmap kernel density estimation used to visualise the relative density of observation points in each calendar month. Darkness of red colours — darker/lighter: higher/lower density of observations. See final 2 paragraphs of Section 3 regarding biases in observation opportunity

subsets commencing from 1990 (our chosen start date) were available from long-established programs but not from more recent initiatives. For example, the recording of protected species interactions in Australian fisheries only began in the early 2000s, and the Redmap project started recording sightings by members of the public in 2009 (https://www.redmap.org.au/). Furthermore, contributed data subsets had diverse end dates because source databases were updated at different intervals, e.g. monthly, yearly or less frequently. Accordingly, data totals for the last 2 years of our study period cannot be construed as a downward trend.

The prominent rise in offshore observations of leatherbacks from about 2015 (Fig. 3) is particularly interesting because it coincides with the implementation of integrated electronic monitoring in some Australian fisheries (for details, see Emery et al. 2019 and references therein). Emery et al. (2019) studied fishers' mandatory logbook records and standardised their catch records by unit effort, then compared the first 2 years with electronic monitoring against the period prior to electronic monitoring. Results showed that the 2 years with electronic monitoring had significant increases for discarded species (unwanted catch) and for protected species.

Based on those results, Emery et al. (2019) inferred that electronic scrutiny might have motivated greater accuracy of reporting. The same rationale could potentially explain the upward trend in reported leatherback interactions from about 2015. Similarly, leatherback interactions prior to electronic monitoring could have been under-reported.

4.2. Geographic distribution of leatherback observations

Our study presents the most comprehensive record to date for leatherback occurrence in Australian waters and indicates that the species has a much wider geographic and offshore distribution around Australia than previously reported (e.g. Limpus & McLachlan 1979). However, we note that some prior studies were, by design, focused narrowly on coastal zones adjacent to the southeast of Australia (Bone 1998, Hays et al. 2023).

It is relevant to ask whether leatherback use of Australian waters may have expanded or changed over recent decades, but no prior study is available for comparison. Our new understanding of broad-scale leatherback distribution around Australia depends substantially on records of fishery interactions with protected species. The latter were not formally collected until the early 2000s, so there is no prospect of obtaining similar data for earlier decades.

Although there have been gear and effort changes, evidence for long-term change in leatherback turtle bycatch can be sought in the Queensland Shark Control Project (QSCP) in southeast Queensland (Limpus & McLachlan 1979, Limpus 2009). Limpus (2009) used QSCP data from the early 1970s to 2004 to indicate a decline in leatherback turtle abundance in the waters off southern Queensland. However, more recent QSCP data from the same region indicate that while a decline in the 1970s and 1980s may have occurred, leatherback bycatch rates in southern Queensland (Sunshine Coast to the New South Wales border) continue to average 1 to 2 (range: 0–7 between 1990 and 2022) interactions per year, with no distinct trend.

An important caveat to our findings arises from the significantly biased availability of potential observers, e.g. along sparsely populated coasts, and across waters with little or no fishing activity, there would be few or no observers. While we cannot ignore this bias, we must also recognise that observational data can support useful insights in conservation science, particularly regarding elusive marine reptiles (e.g. Tomas et al. 2008, Nicolau et al. 2016, Botterell et al. 2020). In some circumstances, bias can be mitigated by employing on-board observers to record the incidental capture of turtles in fisheries (e.g. Casale et al. 2004, 2017), but that strategy was logistically and economically unfeasible for the long temporal span of our study encompassing multiple types of fishery across the vast spatial extent of Australian waters.

Due to biased availability of potential observers, we cannot infer the localised absence of leatherbacks in areas with few or no observations, and we caution that areas without observations might nevertheless be of biological importance for leatherbacks. A useful future exercise would be to develop and test species distribution models for leatherbacks, to examine the theoretical likelihood of additional areas being suitable.

For the development of species-specific conservation management, it would be valuable to identify consistent behavioural patterns and localised seasonal presence of leatherbacks. While this remains an elusive goal, we sought preliminary insight from 2 satellite-tracking studies. Together they showed that post-nesting leatherbacks from Western Pacific and Indian Ocean breeding sites disperse in very diverse directions (Benson et al. 2011, Swaminathan et al. 2019), which has implications for how the species can be managed in Australian waters and the wider region.

4.3. Northeast Indian Ocean leatherback movements

In the northeastern Indian Ocean, 10 leatherback turtles were satellite-tagged at the Andaman Islands, with 4 dispersing southwestwards towards Africa, while 5 moved in broadly southeasterly directions. Of the latter, 1 leatherback reached offshore waters near northwestern Australia and the other 4 might potentially have done the same after their transmissions ended (Swaminathan et al. 2019). However, if leatherbacks are present around northwestern Australia, they would likely remain un-observed due to very sparse human population and low fishery activity. Hence, this is one of the areas around Australia in which low sightings does not necessarily mean low presence of leatherbacks.

The Swaminathan et al. (2019) study indicates that up to 50% of Andaman-nesting leatherbacks could potentially arrive in Australia's northwestern waters about mid-year. They would at that time be located >1000 km distant from mid-year hotspots indicated by our compiled observations off the southwest coast of Australia (Fig. 4). During subsequent non-nesting years (beyond tracking duration), it is plausible that some Andaman females range widely and may move on to use Australia's southwestern waters, while others may potentially disperse across the north of Australia. The movements of Andaman-associated male and immature leatherbacks have not been tracked, but it seems likely that they would share foraging habitat with females.

4.4. Western Pacific Ocean leatherback movements

A large tracking study initiated at Western Pacific leatherback breeding sites (Benson et al. 2011) found that mid-year nesters (n = 44) dispersed predominantly towards the north and northwest, far from Australia, whereas end-of-year nesters (n = 45) dispersed predominantly southwards on diverse routes.

At least 8 of the tracked Western Pacific leatherbacks spent extended periods in waters off the east and southeast coasts of Australia, where they were inferred to be actively foraging based on area-restricted search patterns in their location data (Benson et al. 2011). Additional study subjects appeared likely to have reached the same area after their transmissions ceased, in some cases after they had followed diverse meandering routes about the Tasman Sea between Australia and New Zealand. Many tracks were not individually identifiable in the published map (Benson et al. 2011, their Fig. 1). Still, we can infer that at least 10 to 25% of Western Pacific end-of-year nesters use waters around southeastern Australia during their first post-nesting year.

On the eastern side of Australia, south of about 25° S, our compiled leatherback observations coincide broadly with areas traversed by satellite-tracked Western Pacific post-nesters. However, none of their tracks (Benson et al. 2011, their Fig. 1) extended west into the Great Australia Bight or south around the coast of Tasmania, although both the latter areas were well represented in our compiled observations (our Fig. 1). Therefore we speculate that, after an initial period in Australia's southeastern waters, these leatherbacks likely extend their meandering trajectories further south and further west during their subsequent non-nesting years, i.e. well beyond the duration of tracking in the Benson et al. (2011) study.

In summary, our compiled observations partly coincide with tracked movements of post-nesting Western Pacific and Northeast Indian Ocean leatherbacks, and also extend well beyond the range of published tracks. This suggests that adult females from both subpopulations would likely traverse Australian waters more widely during subsequent years of their respective non-nesting periods, and probably share foraging areas in Australian waters with male and immature leatherbacks (not tracked). Leatherbacks are crucially dependent on long periods of foraging between successive breeding attempts (typically 2—4 yr, range: 1—11 yr; Eckert et al. 2015), reflecting the extended time needed for each animal to regain energy after breeding and accumulate sufficient energy for their next return migration, mating and egg production.

4.5. Recognising government data value and constraints

Our study demonstrates the important environmental value of wildlife data recorded over decades by multiple government agencies in Australia. Their collective efforts underpin the multi-decade overview of leatherback occurrence we have presented. Systematic collection of a comparable dataset by existing research methods would have been logistically and economically unfeasible, due to vast spatial extent, extended timeframe and open ocean conditions.

Australian government agencies tasked with managing various aspects of the environment and (separately) fisheries are numerous and spread across jurisdictional levels, including federal, state and territory governments and statutory authorities for distinct fisheries, the latter being defined variously by geographic region, fishing equipment used, and target species (McPhee 2008). In this complex administrative situation, it was difficult for us to identify custodians of data potentially relevant for our study, and very time-consuming to negotiate separate data-sharing agreements under disparate policy constraints. The latter precluded future sharing of our de-identified merged dataset, a regrettable limitation from a research perspective. It would be valuable if a high-level government agency could take the lead in facilitating research access to wildlife records and environmental data gathered by a plethora of different agencies.

5. CONCLUSIONS

Australian waters are evidently of high importance for foraging leatherbacks, given that prior satellite tracking confirmed that a substantial cohort of post-nesting leatherbacks target Australian waters (Benson et al. 2011, Swaminathan et al. 2019), and our study has confirmed their presence around Australia in all months of the year. We therefore infer that Australian management agencies have crucial roles to play in protecting these endangered animals.

Based on the relative proximity of Western Pacific and Northeast Indian Ocean nesting sites and confirmed post-nesting movements (Benson et al. 2011, Swaminathan et al. 2019), it is likely these 2 subpopulations provide the majority of leatherbacks observed in Australian waters. We do not rule out possible minor contributions from African and Eastern Pacific subpopulations, given that some leatherbacks have been shown to traverse equivalent or greater distances (Benson et al. 2011). Regardless of the precise stock composition, all potentially contributing subpopulations in the Pacific and Indian Oceans are at high risk of extinction (National Marine Fisheries Service & U.S. Fish and Wildlife Service 2020), and therefore all leatherbacks in Australian waters warrant urgent conservation effort.

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