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REVIEW, CONCEPT, AND SYNTHESIS

A review of the importance of south-east Australian waters as a global hotspot for leatherback turtle foraging and entanglement threat in fisheries

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Abstract

Australia's largest sea turtle is the leatherback (*Dermochelys coriacea*). Leatherbacks do not nest, or only rarely, in Australia, and hence receive relatively little research attention. Here we review the knowledge of leatherback turtle occurrence in south-east (SE) Australia, drawing on sightings information as well as satellite tracking data from turtles equipped at their nesting beaches in Indonesia, the Solomon Islands and Papua New Guinea that then travelled to Australia. These data reveal that SE Australia likely provides a globally important foraging area for this species. Sea turtle temperatures assigned to sightings of live leatherbacks, showed 95% were seen at SSTs ≥ 14 °C. Similar to other parts of the world, such as the North Atlantic, the 12–15 °C isotherms likely constrain the seasonal pole-wards migration of leatherbacks searching for their gelatinous prey. Climate warming is likely moving the foraging range of leatherbacks poleward. This study also highlights the vulnerability of this SE Australian population to anthropogenic threats. Of 605 sightings of leatherbacks, 11.6% were of dead individuals, generally washed ashore, in most cases likely after entanglement in fishing gear.

Keywords Bycatch · Marine protected areas · Thermal niche · Conservation management · Pot fisheries · Gill nets

Introduction

Identifying species movements and habitat use lies at the heart of many research efforts to support threatened species conservation management, such as targeted solutions to mitigate threats in high-use areas and designation of conservation areas (e.g. Seminoff et al. 2014; Hazen et al. 2018; Hays et al. 2019). For example, satellite tracking of loggerhead turtles (*Caretta caretta*) in Mexico was used to inform the design of marine reserves (Peckham et al. 2007) and to show the effectiveness of existing reserves in Greece (Schofield et al. 2013). Direct observations have also been commonly used to assess the distribution of species. For example, sightings data of humpback whales (*Megaptera novaeangliae*) and North Atlantic right whales (*Eubalaena glacialis*) revealed high-use areas in the Gulf of Maine and these data contributed to the declaration of the Stellwagen Bank National Marine Sanctuary (Hoyt 2011). However, despite these types of knowledge gains allowing informed conservation management for threatened marine megafauna across the globe (Hays et al. 2019; Sequeira et al. 2019), for many species, there remains limited and/or fragmented distribution information, limiting our response to mitigate threats and to support their recovery.

Leatherback turtles are listed under the IUCN Red List as "vulnerable" globally but "critically endangered" in the Pacific (Wallace et al. 2013a), with major declines in abundance reported for both the western and eastern Pacific (e.g. Tapilatu et al. 2013). In some cases, declines have likely been linked to harvesting of eggs and in other cases due to fisheries bycatch (e.g. Hamann et al. 2006; Laud OPO Network 2020), with leatherback now close to extinction in some areas where there used to be large nesting populations. For example, on the Pacific Coast of Costa Rica nesting leatherback numbers have declined from 1000 + females a few decades ago to only a handful of individuals (Laud OPO Network 2020). In the entire Pacific region, it is now thought

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that there are only a few thousand adult female leatherback turtles, with the key remaining nesting populations in Indonesia, the Solomon Islands and Papua New Guinea (Wallace et al. 2013a).

Leatherbacks almost never nest in Australia (Limpus 2009). There appeared to be very low-density nesting each year during 1973–1983, but there have been only a handful of nesting attempts recorded since then (Limpus 2009). However, parts of Australia are expected to provide important foraging habitat. For example, both satellite tracking data of females from their nesting grounds (Benson et al. 2011) and direct observations (Bone 1998; Limpus 2009) have shown individuals occurring off SE Australia to the coast of New Zealand (Gill 1997). Here we set out to compile records of leatherback turtles off SE Australia and to link these records with remotely sensed data to identify their thermal niche, so that likely long-term changes in their range can be explored. We place the compiled data in the public domain so that ongoing observations can easily be added to this knowledge base and the data made available for national conservation planning. In this way, our review may serve as a template for similar compilations of sightings data for leatherback turtles and other endangered taxa around the world where sightings data are an important source of information on distribution.

Materials and methods

Historical leatherback turtle observations were collated from easily accessible and government-managed databases such as the Australian Living Atlas (ALA) (https://doi.org/10.26197/ala.04514996-0279-49f1-bcce-88aac461b4ed), the Victorian Biodiversity Association (https://vba.biodiversity.vic.gov.au/vba/#/), Tasmanian Natural Values Atlas (https://www.naturalvaluesatlas.tas.gov.au/), the Online Zoological Collections of Australian Museums (https://doi.org/10.26197/ala.3483573f-2f6e-4cce-83cf-1ea67b71724e), and a sea turtle database held at the Tasmanian Museum and Art Gallery. In addition to these sources, local knowledge was sought from the Victorian Fisheries Authority and key industry stakeholders such as local fishers. We note that there is likely to be more observation data available that would assist future iterations of the database.

The following search terms were used to query databases: "leathery turtle", "luth", "leatherback turtle", "leather back turtle" and "*Dermochelys coriacea*". Records were compiled and duplicate records were identified based on similar date ranges, comments, GPS locations, site descriptions and named observers. Given that the ALA had the largest amount of information, where possible these records were identified as the primary observation source noting duplicates from other sources.

Sighting records were categorised into one of two states, either (i) alive or (ii) dead at the time of observation or soon afterwards (< 2 days later). Where there was insufficient information to determine the state of the turtle a third (iii) "unknown" classification was used. In some cases, reports noted if leatherbacks were entangled in fishing gear (nets and ropes) and were subsequently classified into (i) entangled, (ii) not entangled and (iii) unknown. Sighting records were also categorised into (i) observed at sea, (ii) stranded or (iii) unknown if not explicitly stated. There were a number of observations that included somewhat vague descriptions of the date for the leatherback observation. This included such comments as "*sum-1968*" or "*Late Feb 1992*". In these instances, an approximation was used to set a date for the middle of that time period. For example, the summer months include December, January and February, with the 1 January being considered the middle of this time period. We appreciate this definition of date for these records is somewhat arbitrary.

We assigned a sea surface temperature (SST) value to alive records using data from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, https://icoads.noaa.gov/). ICOADS is a widely used global data-base of empirical observations. ICOADS data are provided on a 2-degree (since 1800) spatial grid and 1-degree (since 1960) spatial grid, providing monthly means which are not interpolated or analysed to fill data voids. All figures and statistics were compiled in R v4.2.2 using RStudio v2022.12.0 (R Core Team 2022).

Satellite tracking data for two leatherbacks travelling from their nesting beaches in West Papua, Indonesia, down to SE Australia (reported in Block et al. 2011 and Benson et al. 2011) were downloaded from the Tagging of Pacific Pelagics data-portal (https://mola.stanford.edu/DataLinks/). These were the only two satellite tracks for which raw data were available from a total of 32 turtles tracked from their nesting beaches to the Tasman Sea. We also searched the literature to assess key findings from satellite tracking studies around the world of leatherbacks migrating from their nesting beaches and for examples of focal areas where leatherbacks have been described as being at high risk of bycatch through entanglement, for example, in buoy ropes or gillnets. Identification of entanglement typically came from direct observations of leatherbacks entangled in ropes or nets, both at sea and washed ashore.

Results

We compiled a total of 605 records of leatherback turtles sighted off the coasts of the Australian states of Victoria, Tasmania and South Australia between 1862 and 2022 (Table S1). Of these records, 70 of 605 (11.6%) were of dead leatherbacks (or leatherbacks that died shortly after being sighted) and were typically of individuals washed ashore, while 497 of 605 records (82.1%) were of alive leatherbacks. In the remaining cases, it was not noted if the turtle was alive or dead. Of the 605 observations, 69 records involved entanglement. In some cases, the turtle was rescued by the observer and in other cases the entanglement resulted in the death of the turtle. For example, there are a number of records similar to a 1985 observation where a turtle was "*Entangled in 4 craypot buoy lines. Alive but not well. Brought back to shore, later died*" (Table S1). In other encounters, entangled turtles were released alive such as a 1994 record where a turtle was "*Entangled in craypot lines with only 1 turn of line around flipper. Very vigorous, towing pot away. Pot cut away to release turtle. Alive*" (Table S1). While historically turtles caught in the ocean were sometimes used for bait (e.g. a record from 1934, Table S1) or tethered to be sold as the key ingredient for turtle soup upon reaching the next port (e.g. a record from 1871, (Table S1)), more recent observations have shown observers going to great lengths and cost (loss of fishing gear) to disentangle the turtle, such as a record from 1993 where a turtle was "*Entangled in craypot line. Released alive (lost a pot)*" through cutting buoy lines (Table S1). Leatherback turtles have been of keen interest to museums and historically were actively sought through methods such as harpooning (e.g. a record from 1938). However, current practices have changed to performing autopsies of dead individuals (e.g. a record from 2014). While the majority of observations are of the sighting of only one turtle, there are some instances where multiple individuals were reported, such as described in a record in 1993 where a turtle was "*Badly entangled in cray pot lines. Released alive with 4–5 others. Seen earlier nudging bouys on surface*." (Table S1).

For 150 of the 497 alive records and 65 of the 70 dead records, the month and year of the observations were recorded (Fig. 1a). For the alive records, we were able to assign an ICOADS 2-degree mean sea surface temperature (SST) in 120 cases. In the remaining records there was no ICOADS data for that location and date. Below and in Fig. 2c, d, we describe the analysis of the SST associated with observations.

Two satellite tracked leatherbacks departed from Indonesia in February 2007 around 20 days apart at the end of their nesting season and travelled generally southwards, being off the coast of Victoria from October to December. At the most southerly locations of these tracked individuals, i.e. while they were off the east coast of Victoria and in Bass Strait, a body of water between southern Victoria and northern Tasmania, the SST at the location of the turtles varied from 14 to 18.5 °C based on ICOADS 1-degree SST (Fig. 1b).

Using the proportion of alive strandings in each month, we generated the expected number of dead strandings that would occur each month if dead strandings followed the same seasonal distribution. We then compared the observed versus expected monthly numbers of dead strandings using a G-test and in this way examined if the alive versus dead records followed the same seasonal pattern. There was no significant difference in the seasonal occurrence of alive versus dead leatherbacks ($G_{11}=9.85$, $P=0.54$), with a similar number of dead leatherbacks recorded in winter and summer months (Fig. 2a, b). Alive records of leatherback peaked in January, i.e. the middle of the austral summer, and were at a minimum in August and October, i.e. during the austral winter and spring. Records of dead leatherbacks were slightly more evenly distributed across the year, although

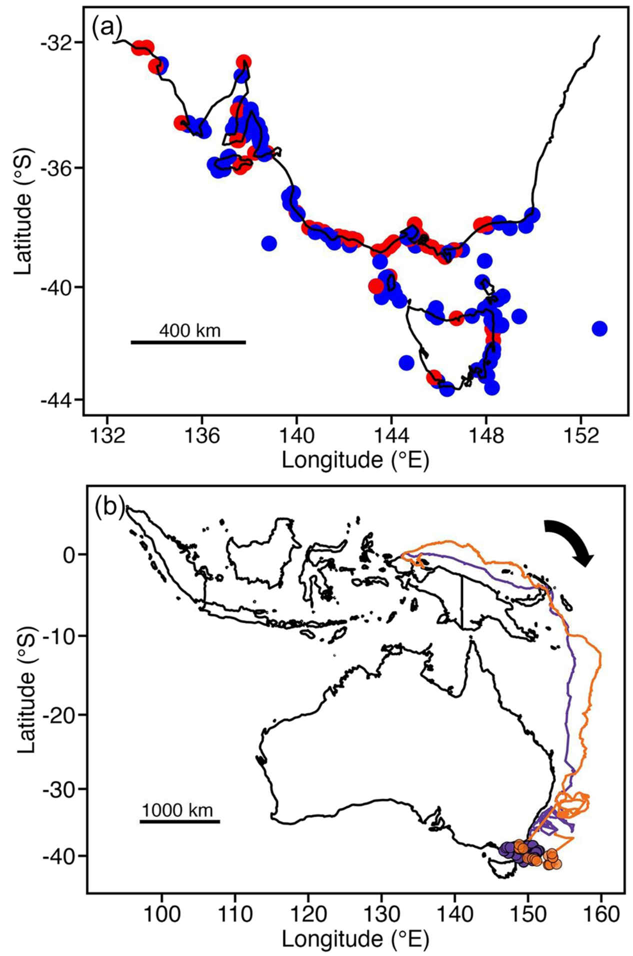

Fig. 1 **a** Location for 150 alive (blue points) and 65 dead leatherback turtles (red points) recorded off the coasts of Victoria, Tasmania and South Australia between 1862 and 2022. **b** The tracks of two leatherback turtles (toppID: 2,607,015 (orange) & 2,607,012 (purple)) equipped with Argos satellite tags on their nesting beaches in Indonesia (from Block et al. 2011). Lines show migration routes and points were plotted for turtles when they were off the Victorian coastline between October to December 2007. During this time the sea surface temperature ranged from 14 to 18.5 °C. Black arrow shows direction of travel

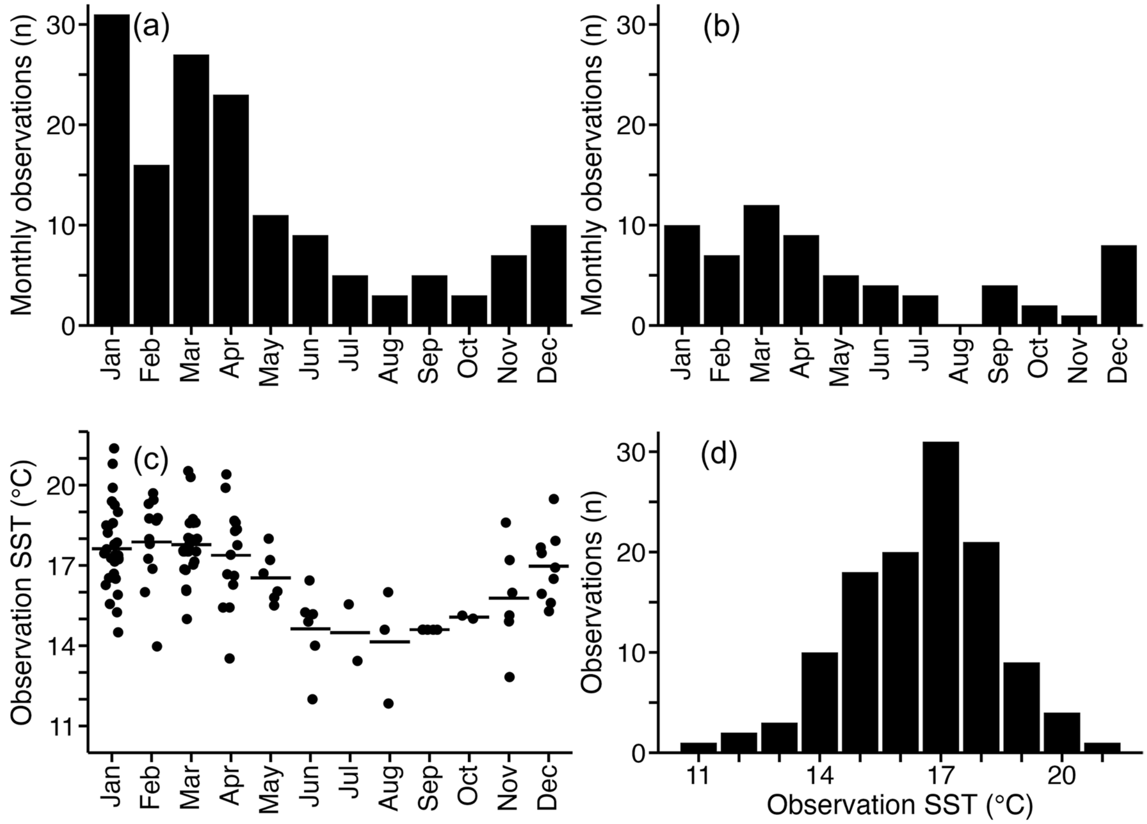

Fig. 2 Seasonal occurrence of **a** alive and **b** dead leatherbacks in SE Australia. **c** The ICOADS 2-degree sea surface temperature (SST) associated with alive records, with horizontal lines showing the mean observation SST associated with records each month. 95% of alive-at-sea records occurred at SSTs ≥ 14.0 °C. **d** The frequency distribution of SSTs associated with each alive record, shows that leatherback turtles were most commonly observed between 17 and 18 °C

with no observations in August. Sea surface temperature information was available for 120 alive records, with 95% of records occurring at SSTs of ≥ 14 °C (Fig. 2c, d). There was only one alive-at-sea record at a SST < 12 °C (11.8 °C) and two between 12 and 13 °C.

Across the globe, long migrations have been noted for nesting female leatherbacks (Fig. 3), with entanglement highlighted both close to nesting beaches (e.g. Trinidad) as well as on distant foraging grounds (e.g. SE Australia and the NW Atlantic) (Figs. 3 and 4).

Discussion

In Australia, several species of sea turtles nest, often in very large numbers, and are a focus for extensive research and conservation efforts. Some key areas for conservation work include green turtles nesting at Raine Island (Great Barrier Reef), the largest green turtle rookery in the world (Booth et al. 2021 and references therein), and flatback turtles that are endemic to the Australasian region (Whiting et al. 2009). It is perhaps unsurprising that leatherbacks receive less attention because they rarely nest in the region. Studying foraging leatherbacks in Australia at sea is not straightforward since the animals likely occur at a low density making directed observation difficult. We can make a very tentative estimate of the likely numbers of leatherbacks visiting SE Australia using information on nesting numbers and movements of leatherbacks at rookeries in Indonesia, the Solomon Islands and Papua New Guinea (Wallace et al. 2013a) combined with satellite tracking data (Benson et al. 2011). Of 44 winter nesting leatherbacks tracked from this nesting region (Benson et al. 2011), 32 (73%) travelled southwards to the Tasman Sea region, with about two-thirds of these travelling to SE Australia and one-third to New Zealand (Benson et al. 2011). So around 50% of winter nesting turtles travelled to SE Australia. The most recent IUCN estimates are that there are around 5000 nests per year in the west Pacific and that the species is critically endangered (Wallace et al. 2013a). If we assume 50% of these are winter nests (i.e. 2500 nests) and assume a mean clutch frequency of 5 nests per individual (Wallace et al. 2013a) this equates to 500 winter nesters per year. If we then assume a remigration interval (the interval between breeding seasons) of around 3 years

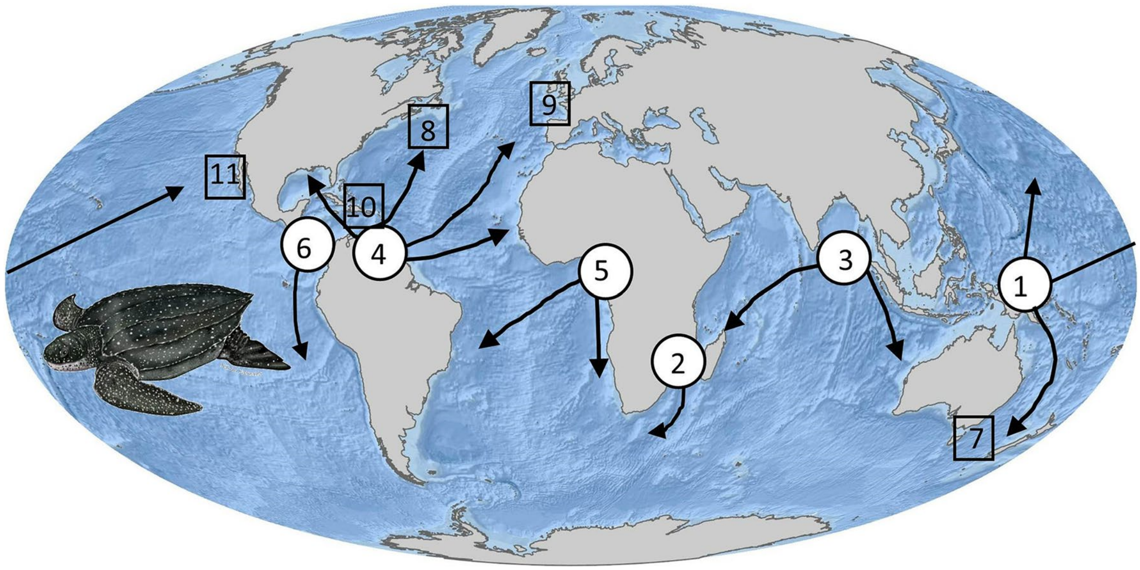

Fig. 3 General patterns of movement of post-nesting female leatherbacks revealed by satellite tracking and occurrence of entanglement. Circles represent nesting regions where satellite tags have been attached. Nesting areas: 1 = Indonesia, the Solomon Islands and Papua New Guinea (Benson et al. 2011); 2 = South Africa (Luschi et al. 2006; Fossette et al. 2014); 3 = Andaman and Nicobar Islands (Swaminathan et al. 2019). 4 = French Guiana and the Caribbean (Fossette et al. 2014), 5 = Gabon, West Africa (Fossette et al. 2014). 6 = Pacific Coast of Costa Rica (Shillinger et al. 2008). Squares are hotspots where bycatch entanglement in nets and fixed lines (e.g. pot fisheries) have been highlighted. Identification of entanglement typically came from direct observations of leatherbacks entangled in ropes or nets both at sea and washed ashore. 7 = SE Australia and New Zealand (this study, Bone 1998); 8 = NW Atlantic (including Nova Scotia and Massachusetts) (Hamelin et al. 2017; Dodge et al. 2022); 9 = northern Europe (Witt et al. 2007); 10 = Trinidad (Caribbean) (in Dodge et al. 2022); 11 = California coast (Hazen et al. 2018). Leatherback image credit: NOAA Fisheries. Bycatch in longline fisheries likely extends across the world's oceans (Fossette et al. 2014)

(Lontoh et al. 2013), this annual nesting number translates to a total of about 1500 adult female winter nesting turtles (i.e. 3×500). If the ratio of turtles travelling to SE Australia is maintained at around 0.5, and assuming a balanced adult sex ratio (i.e. equal numbers of males as females) and that the same number of sub-adult turtles migrate to SE Australia, then we can estimate that 0.5 (1500 females + 1500 males + 1500 subadults) = approximately 2250 individuals visiting the region each year. These values are clearly very tentative and could be refined when more recent census data and/or tracking data are available. Nevertheless this calculation suggests that appreciable numbers of leatherbacks likely visit the SE Australia region annually, potentially over 2000 turtles, and hence this region has important conservation value especially given the critically endangered status of leatherbacks in the region.

Our results reinforce and extend the conclusion of Benson et al. (2011), from tracking data alone, that the regions around SE Australia and NZ are important foraging hotspots for the species both in the Pacific and likely globally. Clearly the sightings records only represent a tiny fraction of the individuals likely using this region. Certainly not all sightings will be reported. For example, in public lectures in Victoria, we have received information from attendees that they have seen leatherbacks offshore, but have not reported their sightings. Likewise Bone (1998) reported that 44 of 62 fishermen and charter boat operators interviewed in Tasmania had encountered leatherbacks.

Given the likely importance of the region for leatherbacks, it is worrisome that 11.6% of sightings records were of dead turtles, with certainly some of these dead turtles found entangled in fishing nets or ropes. Entanglement in lobster pot buoy ropes was also reported for leatherbacks in Tasmania by Bone (1998), with an estimate of 75% of entangled turtles being released alive. Bone (1998) also reported interviews with fishermen operating in a Tasmanian driftnet fishery indicating that 100 s of leatherbacks were found entangled in nets, but further details were lacking. So there is certainly the suggestion that interactions of leatherbacks with fishing gear may be high, and often unreported, in the region. Entanglement is likely also an important anthropogenic source of mortality for leatherbacks around the world. Set against this backdrop of a global threat, focal areas where the density of foraging leatherbacks is high may also be important hotspots for bycatch. For example, Nova Scotia (Canada) is an important foraging area for leatherbacks in the Atlantic (James et al. 2005) and they are often found in this region entangled in fixed fishing gear (nets and ropes associated with pot fisheries) (James et al. 2005; Hamelin et al. 2017). Entanglement is also prevalent with

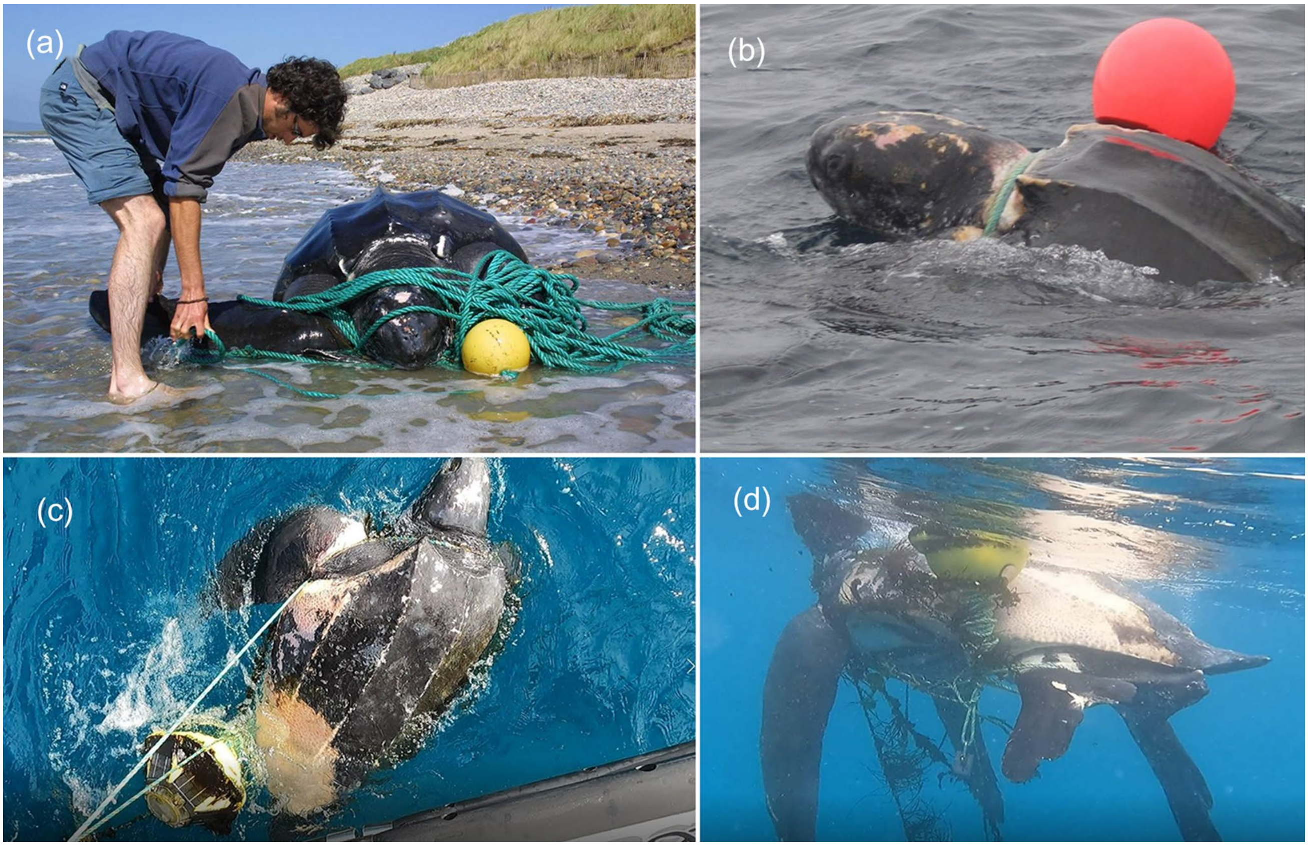

Fig. 4 Examples of leatherback turtles entangled in buoy ropes from around the world. **a** a leatherback turtle washed ashore in Ireland (northern Europe). Photo credit Shay Fennelly **b** a leatherback turtle entangled in a buoy rope at sea off Ireland. This turtle was released alive. Photo credit Oliver Buckley. **c** and **d** a leatherback turtle entangled in a buoy rope in SW Victoria (Australia) in 2022. This turtle died soon after being found entangled. Photo credit Zoos Victoria

leatherbacks off Massachusetts (USA) (Dodge et al 2022) and entanglement and boat strikes were identified as important sources of mortality for leatherbacks around the Canary Islands (North Atlantic) (Orós et al. 2021). Bycatch in artisanal coastal gillnet fisheries near nesting beaches in Trinidad and the Guianas has been estimated at 1000 – 3000 leatherbacks yr^{-1} (in Dodge et al. 2022). The threat of bycatch in fisheries, including longline fisheries, for leatherbacks most probably extends widely across the world's oceans (e.g. Wallace et al. 2013b; Fossette et al. 2014).

While entanglement in fishing gear is clearly an important threat to leatherbacks at sites around the world, including Australia, mitigating this threat is not straightforward. Attempts to reduce bycatch in gillnet fisheries through the addition of lights to the gear have shown some promising results (Allman et al. 2021). It has been suggested that ways to reduce bycatch mortality in buoy ropes used in pot fisheries may be to reduce the soak time of gear, i.e. the interval between checking the gear (Dodge et al. 2022). Reducing the soak time may increase the chances that incidentally caught leatherbacks can be released alive. Another proposed method has been the use of "ropeless" fishing, where throughout most of a deployment the marker buoys stay near the seabed and are only released, with the buoy rope unfurling, just before retrieval (Dodge et al. 2022). However, widespread adoption of these fishing approaches may be costly and not straightforward to achieve.

Given that leatherbacks may be widely dispersed at low densities across their foraging grounds, making directed observations (e.g. from boats or aerial surveys) at this time may not be cost-effective. Reports from the public, i.e. citizen science, may therefore be an efficient method of collecting sightings data and provide important information to allow foraging hotspots to be identified (e.g. Houghton et al. 2006). To increase the number of reports in such citizen science projects, one approach is to raise public awareness and make reporting as easy as possible, for example through free-to-down mobile phone apps, that have been successfully used in citizen science projects with other taxa (Frigerio et al. 2017).

It has previously been shown that leatherbacks are generally seasonal visitors to high latitudes, occupying such areas when the water is above some threshold temperature, with turtles feeding on gelatinous zooplankton. For example, in coastal bays in the UK and France, hotspots for leatherback turtle sightings are areas where summer blooms of the large barrel jellyfish (*Rhizostoma octopus*) occur (Houghton et al. 2006). Off Nova Scotia (Canada), leatherbacks are seasonal visitors and have been observed feeding on large lion's mane jellyfish (*Cyanea capillata*) (James and Herman 2001; Heaslip et al. 2012). Off SE Australia, blooms of jellyfish, including the large blue blubber jellyfish (*Catostylus mosaicus*), regularly occur (Fancett 1986). In addition, recent work has shown that the region may support other kinds of gelatinous plankton, including salps and appendicularians, that may provide food for other vertebrate predators in the region such as penguins (*Eudyptula minor*) (Cavallo et al. 2018). While leatherbacks often feed on large jellyfish, they may equally feed on high densities of much smaller gelatinous prey (Fossette et al. 2012). As such there are likely a range of types of gelatinous zooplankton for leatherbacks in SE Australia.

At some other high latitude foraging sites (e.g. north Europe, Witt et al. 2007), relatively more dead leatherbacks are found stranded on beaches in the winter, when the water is cooler. This pattern presumably reflects the fact that a dead turtle may drift for some time before being washed ashore and/or moribund turtles that are alive may still, unusually, be found at high latitudes in winter. However, we found that dead turtles occurred around the year, in more-or-less the same seasonality as alive sightings, suggesting that the time before dead leatherbacks are sighted, usually washed ashore, may not be long. In some cases entanglement may contribute to sightings in winter SE Australia. For example, one of the records in our data-base was a leatherback found alive at sea in SW Victoria in July 2022 dragging a net but also entangled in an anchored buoy rope. The turtle was brought ashore but died soon after. Presumably, due to dragging the net, the turtle was unable to migrate northwards as the ocean cooled in southern Australia.

In the NE Atlantic, it has been suggested that the 15 °C isotherm may be the thermal barrier that limits leatherback northerly movements and constrains their seasonal occupation of high latitudes to summer months (McMahon and Hays 2006). This isotherm limit was revised to 12 °C by Witt et al. (2007). These different isotherms will encapsulate different proportions of sightings at high latitudes, with relatively high numbers of records above 15 °C and only a few additional records between 12 and 15 °C. The leatherback turtle records in SE Australia are broadly consistent with this isotherm range limit, with 95% of the alive-at-sea records occurring at SSTs $\geq$ 14.0 °C. This evidence suggests that, around the world, the occupation of high latitudes by leatherbacks is generally constrained by temperatures around 12–15 °C, i.e. there is thermal niche conservatism for this species in different ocean basins. Warming of the oceans in the last 60 years will have moved this thermal limit for leatherback pole-wards (McMahon and Hays 2006), i.e. the foraging range of leatherbacks has likely expanded in the last century. Certainly SE Australia is a region where the velocity of climate change (i.e. the pace of movement of isotherms) is particularly fast (Burrows et al. 2014). So it is likely that SE Australia is lying further and further within the seasonal foraging range for leatherbacks.

In summary, our review highlights that SE Australia is an important foraging site for leatherback turtles. We recommend an important future step to improve our understanding of leatherbacks in this region is to raise the public awareness of this species as part of a citizen science approach. This approach would increase the number of sightings records. In this way, key sightings hotspots within this general region might be identified, as has been achieved using this approach in other parts of the world (e.g. Houghton et al. 2006), thereby helping to direct targeted conservation efforts.

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Author contributions GCH conceived the project. JT and MM assembled the sightings data. JT assembled the sea surface temperature data. JT and GCH analysed the data. GCH led the writing with contributions from all authors.

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Data availability All the raw sightings data are available in the Supplementary Information that accompanies this article.

Declarations

Conflict of interest No conflicts of interest or competing interests to declare.

Ethical approval The work only used data extracted from the literature.

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