



Disentanglement network data to characterize leatherback sea turtle *Dermochelys coriacea* bycatch in fixed-gear fisheries

Kara L. Dodge^{1,*}, Scott Landry², Bob Lynch², Charles J. Innis^{1,3},
Katherine Sampson⁴, Doug Sandilands², Brian Sharp^{2,5}

¹Anderson Cabot Center for Ocean Life, New England Aquarium, Boston, MA 02110, USA

²Center for Coastal Studies, Provincetown, MA 02657, USA

³Animal Health Department, New England Aquarium, Boston, MA 02110, USA

⁴National Marine Fisheries Service, Greater Atlantic Region, Gloucester, MA 01930, USA

⁵Present address: International Fund for Animal Welfare, Yarmouth Port, MA 02675, USA

ABSTRACT: To characterize sea turtle bycatch in fixed-gear fisheries in Massachusetts, USA, we analyzed a 15 yr dataset of entanglement reports and detailed documentation from disentanglement operations. Almost all (272) of the 280 confirmed entanglements involved leatherback turtles *Dermochelys coriacea*. The majority of turtles were entangled in actively fished (96 %), commercial (94 %) pot/trap gear with unbroken/untriggered weak links, specifically the buoy lines marking lobster, whelk, and fish traps. Most reports came from recreational boaters (62 %) and other sources (26 %), rather than commercial fishers (12 %). Leatherback entanglements occurred from May to November, with peak reporting in August, and included adult males, adult females, and subadults. All entanglements involved the turtle's neck and/or front flippers, with varying degrees of visible injuries; 47 entangled leatherbacks were dead in gear, 224 were alive at first sighting, and 1 case was unknown. Post-release monitoring suggested turtles can survive for days to years after disentanglement, but data were limited. While the observed entanglements in our study are low relative to global bycatch, these numbers should be considered a minimum. Our findings are comparable to observed numbers of leatherbacks taken in Canadian fixed-gear fisheries, and represent just one of multiple, cumulative threats in the North Atlantic. Managers should focus on strategies to reduce the co-occurrence of sea turtles and fixed-fishing gear, including reductions in the number of buoy lines allowed (e.g. replace single sets with trawls), seasonal and area closures targeted to reduce sea turtle–gear interaction, and encourage the development of emerging technologies such as ‘ropeless’ fishing.

KEY WORDS: Bycatch · Leatherback turtle · Fixed-gear fisheries · Entanglement · Pot/trap · Injury · Disentanglement · Post-release monitoring

1. INTRODUCTION

Incidental capture, or bycatch, of non-target species in fisheries gear is a critical global conservation issue (Żydelski et al. 2009, Lewison et al. 2014). Bycatch has been implicated as a primary cause of pop-

ulation declines across a multitude of marine taxa, including marine megafauna such as sharks, marine mammals, seabirds, and sea turtles (Lewison et al. 2004, Read et al. 2006, Oliver et al. 2015). Industrial-scale fisheries, mainly longlines, trawls, and gillnets, have been the focus of most bycatch analyses to date

*Corresponding author: kdodge@neaq.org

(Wallace et al. 2010, Lewison et al. 2014, Casale et al. 2017), with the exception of large whales in pot/trap gear (Johnson et al. 2005, Knowlton et al. 2012, Jannot et al. 2021). In US fisheries, bycatch data are typically collected by trained fishery observers onboard commercial fishing vessels, and these data form the basis for fishery bycatch assessments (e.g. Murray 2011, Martin et al. 2015, Swimmer et al. 2017). However, some fisheries cannot accommodate observers due to logistical constraints, such as size of the vessel, allowing for exemptions from federal requirements mandating observer coverage. Since bycatch events are usually rare relative to overall fishing effort (Wallace et al. 2013), it can be challenging to implement adequate fishery observer coverage, especially in large-fleet fisheries. Observer-based data collection may also be inadequate depending on how the gear is fished (e.g. tended vs. untended fisheries).

In waters of Massachusetts (USA), a number of rope-based fisheries coexist, using gillnet and pot/trap gear types (i.e. fixed-gear fisheries). These fixed-gear fisheries are passive, relying on the target species to move towards the gear, in contrast to active gear that pursues targets (e.g. trawls, dredges). Fishers set out the gear and return to haul it at a later time, so the pots/traps or nets are not tended during the time period between setting and hauling. Fixed-gear fisheries use vertical buoy lines to connect the weighted gear (pots/traps or nets) on the seafloor to a surface buoy (Fig. 1), usually with enough scope to the buoy line to account for tides. These fisheries harvest a variety of species, with gillnets catching primarily fish, and pot/trap fisheries targeting American lobster *Homarus americanus*, channeled whelk *Busyconotypus canaliculatus*, black sea bass *Centropristis striata*, and scup *Stenotomus chrysops*. The lobster pot fishery is the largest fixed-gear fishery in Massachusetts. For example, in 2018 there were 812 active commercial fishers, who deployed approximately 82 000 vertical buoy lines (Massachusetts Division of Marine Fisheries [DMF] Fisheries Statistics Program; <https://www.mass.gov/orgs/division-of-marine-fisheries>). The whelk and fish pot fisheries are substantially smaller in scale, consisting of 80 and 72 active commercial fishers who deploy approximately 8300 and 2500 buoy lines, respectively. The gillnet fishery is small and declining, with approximately 132 net sets deployed in 2018, representing 132 buoy lines (Massachusetts DMF Fisheries Statistics Program).

The Massachusetts DMF conducts 77 observer trips yr^{-1} in the lobster fishery and 6 trips yr^{-1} in the whelk pot fishery, which represents <1 % coverage in both fisheries. Despite no observations of entangle-

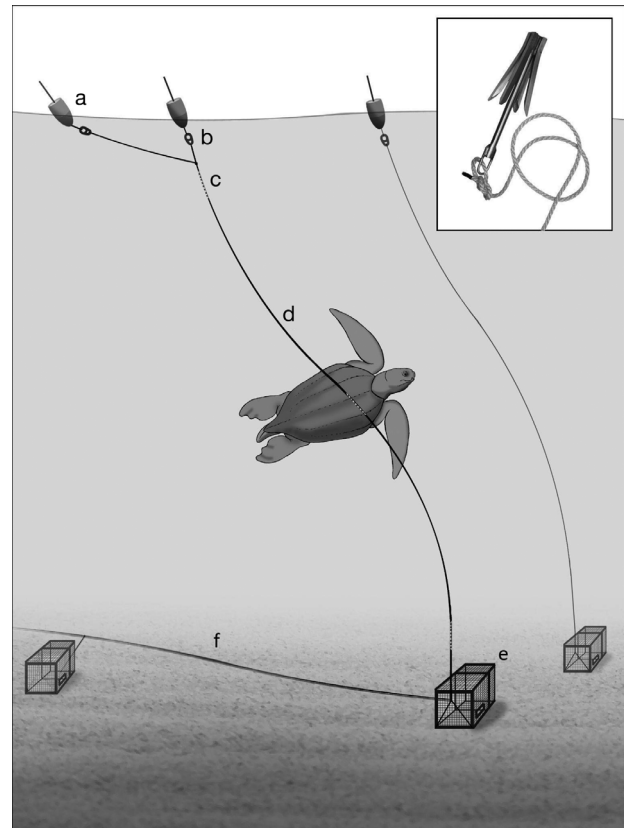


Fig. 1. Fixed pot/trap gear typically seen during leatherback entanglement events in this study (not drawn to scale). Elements include: (a) bullet buoys to mark gear set location, (b) weak links, (c) rope markings on (d) buoy lines, (e) pots/traps, and (f) groundline between pots/traps of a trawl. Inset: Modified grapple used to access buoy line beneath entangled turtles and to haul weighted gear

ments during observer trips, opportunistic entanglement reports demonstrate that marine megafauna can become ensnared in the ropes used in fixed-gear fisheries, including the buoy line (Johnson et al. 2005, Knowlton et al. 2012, Hamelin et al. 2017). The Atlantic Large Whale Disentanglement Network, led by the Center for Coastal Studies (CCS), was formed in 1994 in response to opportunistic whale entanglement reports in fixed-gear fisheries. In 2005, the National Marine Fisheries Service (NMFS), DMF, and CCS formed the Massachusetts Sea Turtle Disentanglement Network (MaSTDN) to address ongoing reports of sea turtle entanglements in fixed gear. This network infrastructure has allowed for baseline data collection on fixed-gear fisheries bycatch.

Fixed-gear fisheries and aquaculture operations in Massachusetts overlap with foraging and migration habitats of 4 threatened and endangered sea turtle species, including the North Atlantic green sea turtle

Chelonia mydas distinct population segment (DPS), Northwest Atlantic Ocean loggerhead sea turtle *Caretta caretta* DPS, Kemp's ridley sea turtle *Lepidochelys kempii*, and leatherback sea turtle *Dermochelys coriacea* (Lazell 1980). Foraging leatherback turtles are resident in coastal and shelf waters for up to 4 mo during boreal summer and fall (Dodge et al. 2014) when multiple fixed-gear fisheries (pot/trap, gillnet) are active. The extensive movements and expansive use of the water column in this region by leatherbacks as they feed on gelatinous zooplankton from surface to seafloor (Dodge et al. 2014, 2018) may lead to encounters with co-occurring fishing gear in the water column.

To understand sea turtle bycatch and mortality in fixed-gear fisheries, and identify priority conservation actions, we analyzed a 15 yr dataset from Massachusetts maintained by MaSTDN. Data included confirmed sea turtle entanglement reports, as well as detailed information and documentation (Fig. 2) from disentanglement responses by trained members of the MaSTDN. We describe reporting sources, disentanglement response methods and outcome, seasonal and geographic patterns of entanglement reports, turtle demographics, entanglement characteristics and injuries, and gear types. We also discuss current and proposed mitigation measures for marine megafauna entanglement in buoy lines of fixed-gear fisheries and aquaculture farms.

2. MATERIALS AND METHODS

2.1. Entanglement reports

Between 2005 and 2019, sea turtle entanglements were documented by the MaSTDN and the CCS Marine Animal Entanglement Response team (hereafter, CCS) based in Provincetown, Massachusetts. We solicited entanglement reports from mariners through targeted outreach events and printed material to the commercial fishing industry, recreational boaters, whale watch operators, military personnel, harbor masters, and research teams. Outreach efforts remained relatively constant throughout the study period, and stressed immediate reporting of entanglement sightings with the reporting party (RP) standing by entangled turtles at a safe distance until trained responders arrived. We encouraged RPs to report entanglements to the CCS hotline (1-800-900-3622) either directly, or indirectly via partners in the region (e.g. United States Coast Guard, NMFS, stranding network organizations). We confirmed entanglement

reports through direct observation by CCS, RP photo/video documentation, detailed description from an experienced RP, or interviews with inexperienced RPs using standardized, neutral questions.

We defined entanglements to include live and dead turtles at sea with entanglement materials, most commonly line or rope (hereafter used interchangeably), wrapping any body part. All entanglements were considered life-threatening without intervention. We did not include turtles with entanglement scars only (no entanglement materials) or entanglements from observer programs, strandings, or free-swimming entrapments in fish weirs. Entanglement reports to the CCS hotline were primarily derived from continental shelf waters of Massachusetts (41°–42° N, 70°–71° W).

2.2. Entanglement response

The MaSTDN entanglement responses included disentanglement, defined here as the removal of all entangling gear from live turtles, collection of detailed data and documentation during the disentanglement event, and inspection or retrieval of entangled carcasses at sea. Prioritization was given to live turtles when response resources were limited. Trained MaSTDN responders conducted disentanglement operations, using methods adapted from CCS whale disentanglement techniques (IWC 2013). Entanglement response prioritized human safety, turtle safety, and documentation of the event. All responders were equipped with personal safety equipment, and per response protocols, no personnel entered the water during disentanglement events. We conducted disentanglement activities from a variety of small boat platforms, with preference given to vessels with a low freeboard that enabled easy access to entangled turtles at the surface.

Disentanglement of a turtle involved the following: (1) assessing the entanglement, (2) establishing a control line to the entangling gear (Fig. 3A), (3) maintaining the turtle at the surface alongside the vessel (Fig. 3B), (4) collecting data on the turtle and its entanglement (Fig. 3C), and (5) unwrapping the entangling gear (Fig. 3D). The addition of a control line using a grapple (Figs. 1 & 3A), applied to any weighted gear on the turtle, was deemed a critical aspect of disentanglement. Grappling gear beneath the turtle allowed it to maintain its position at the surface for respiration, ease the weight of the bottom gear and potential tissue damage to the turtle, and keep it within reach of responders. Cutting entan-

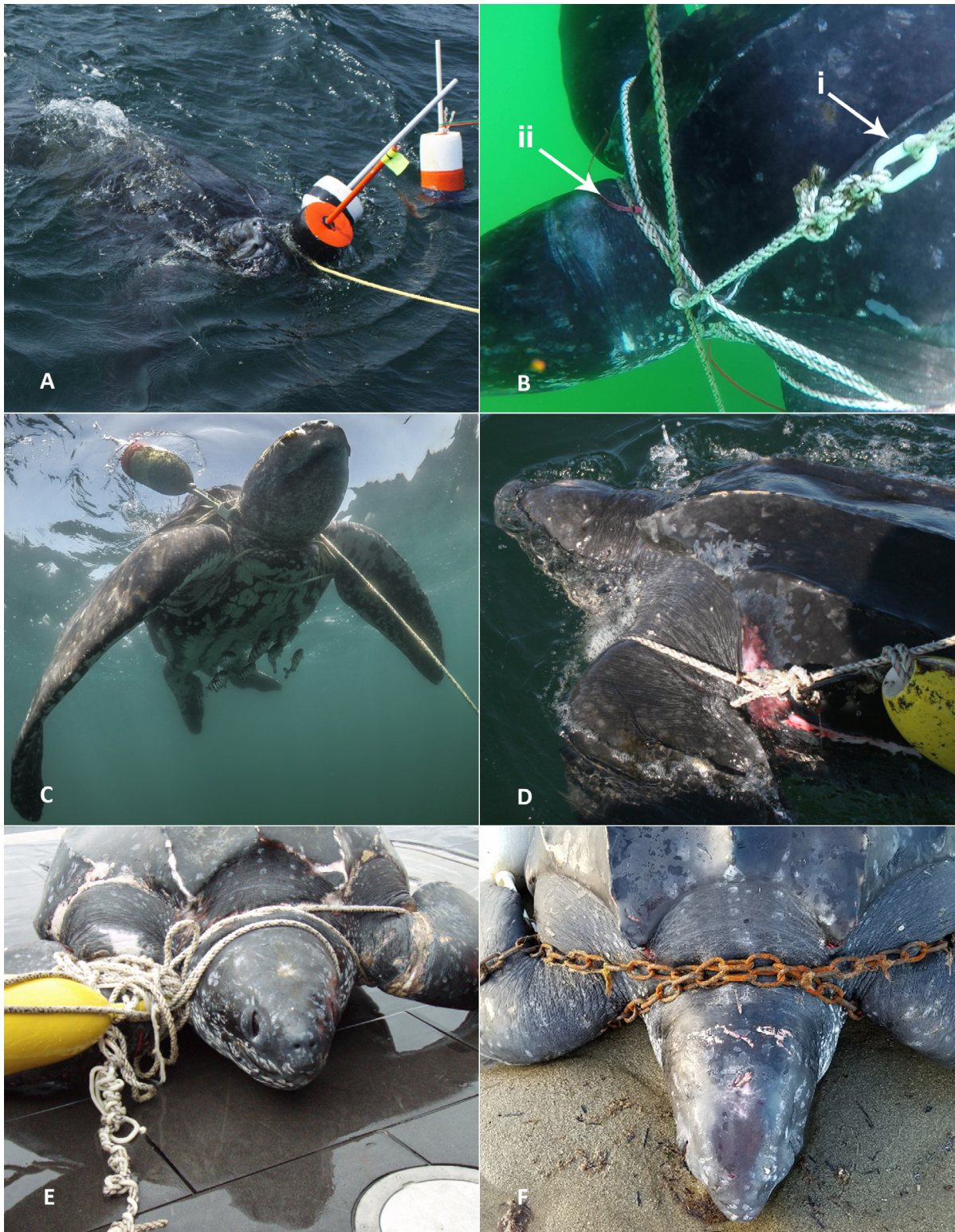


Fig. 2. Entangled leatherback turtles. (A) Leatherback with primary entangling gear impinged on 2 other gear sets. (B) Entanglement showing gear with weak link (i) and line markings (ii) that indicate gear type and area fished. (C) Typical case of a leatherback turtle anchored in gear with line wrapping the neck and both front flippers. (D) Common entanglement wounds include wrapping injuries and carapace abrasions. (E) Serial entanglement case, with pressure necrosis wounds on the left front flipper from an entanglement 19 d prior. (F) Dead leatherback entangled in a 3/8" (0.95 cm) galvanized boat mooring chain

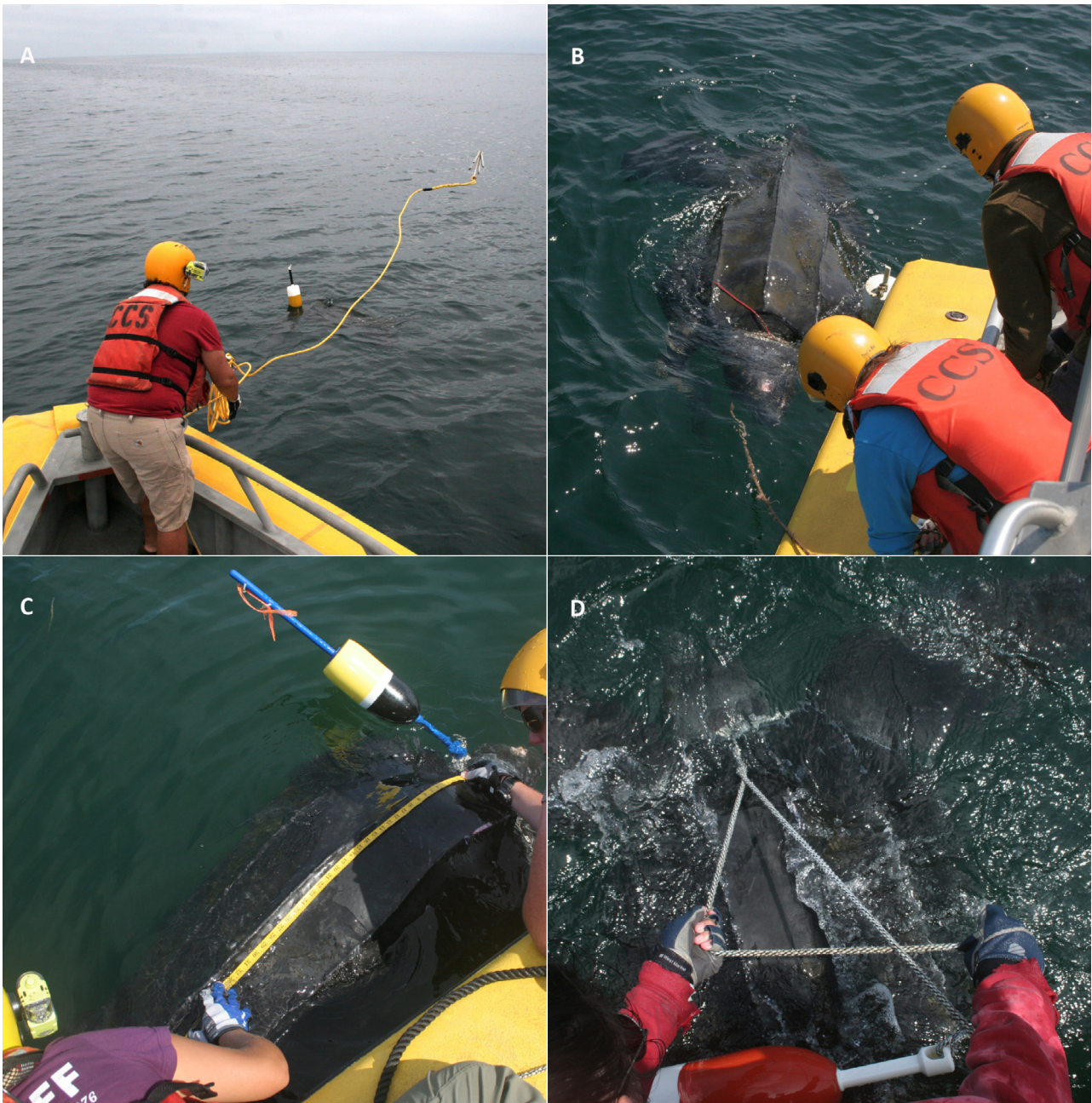


Fig. 3. Disentanglement activities, including: (A) establishing a control line to the entangling gear, (B) maintaining the turtle at the surface alongside the vessel, (C) collecting data on the turtle and its entanglement, and (D) unwrapping the entangling gear

gling gear was generally avoided so as to minimize potential injury to turtles, avert premature release of turtles that had not been fully disentangled, and to prevent creation of ghost gear. A disentanglement was considered successful if all life-threatening gear was removed from the turtle. Whenever possible, the entangling gear was hauled, documented, and reset intact.

MaSTDN was authorized for response through a permit from the US Fish and Wildlife Service to the Sea Turtle Stranding and Salvage Network (STSSN). The STSSN, including CCS, was also authorized for response in the marine environment via 2 NMFS rules: NOAA 50 CFR Part 222.310 (endangered sea turtles) and NOAA 50 CFR Part 222.206 (threatened sea turtles).

2.3. Data collection and analysis

Data collection included information about the event (date, time, location), turtle (species, size, sex, condition, tags, injuries, individual identity), and characteristics of the entangling material (gear type, color, estimated line diameter, entanglement configuration). To distinguish actively fished gear from marine debris, or 'ghost gear', we made the assumption that traps with current-year trap tags were being actively fished. We also made visual assessments of biofouling on the buoys of confirmed pot gear ($n = 126$) since the buoy was the most commonly documented part of the gear, and used a biofouling threshold to evaluate gear in the absence of trap tag information as either actively fished ($<30\%$ biofouling) or debris ($\geq 30\%$ biofouling). Since trap tags are attached to the weighted gear, we were only able to access tag data if the gear was light enough to hand-haul or if we had access to a hydraulic pot hauler ($n = 56$). All data were entered into the CCS entanglement database and used to populate the NMFS standardized Sea Turtle Entanglement Report Form (STERF; see the Supplement at www.int-res.com/articles/suppl/n047p155_supp.pdf). For most cases, additional documentation included photographs and video (surface and/or sub-surface) of all body parts (entangled and non-entangled) (Fig. 2). In some cases, fishing gear analysts inspected the retrieved or documented gear sets to ascertain gear type and target species.

We obtained size and sex information for turtles when field conditions were favorable. Leatherback curved carapace length (CCL) was measured in the water alongside the vessel (Fig. 3C) or on the vessel deck, using a flexible measuring tape. In some cases when CCL could not be measured in the water, straight carapace length (SCL) was measured by holding the tape above the carapace, and then converted to CCL using the methods described by Avens et al. (2009). In-water measurements of live turtles likely contained some error due to sea state and turtle activity level. We assumed a conservative margin of error in our measurements of ± 5 cm, based on the average difference in cases with multiple measurements for 1 individual within a single season ($n = 8$ cases; mean \pm SD = 1.8 ± 1.8 cm). The average size for an adult leatherback is 145 cm CCL (Eckert 2002), therefore we classified turtles as 'adult' for CCL ≥ 150 cm and subadult for CCL ≤ 140 cm. Turtles with CCL measurements between 140 and 150 cm were classified as unknown age class. We sexed adult turtles (CCL ≥ 150 cm) through our direct observations in the field using external features (e.g. tail length,

penis extrusion), necropsy, nesting beach tags, or through subsequent expert review of photo/video documentation of the tail region.

We mapped the spatial distribution of leatherback entanglements off Massachusetts with QGIS v3.4 (QGIS Development Team 2017), and entanglement data were analyzed in R version 3.6.3 (R Core Team 2020). We used linear regression to determine if annual entanglement cases have increased over the study period. All statistical tests were performed at a significance level of $\alpha = 0.05$.

2.4. Injury assessment

We documented turtle behavior and activity level, and made assessments of visible injuries for all live cases that had comprehensive documentation consisting of high quality photographs and/or video of all major body areas, including head/neck, carapace, plastron, and all flippers and flipper insertions ($n = 88$). Each body area was assessed for the presence or absence of fresh lacerations and/or discoloration, and injuries were correlated with the presence or absence of entangling gear. We used the NMFS post-interaction mortality criteria (NMFS 2017) to categorize each case as low risk of mortality (Category 1, 10 % risk), intermediate risk of mortality (Category 2, 50 % risk), or high risk of mortality (Category 3, 80 % risk). We used post-release outcome data from 16 individuals to validate our determinations. For 9 entanglement cases that had been previously assessed by NMFS (Upite et al. 2019), we compared our results to ensure consistency in category assignment.

2.5. Post-release monitoring

We used electronic tags to conduct post-release monitoring of 10 disentangled turtles between 2007 and 2020. From 2007 to 2009, 7 disentangled turtles were equipped with Wildlife Computers model MK10-AF and MK10-A ARGOS-linked satellite tags; detailed tagging methods and results are described by Dodge et al. (2014). In 2019, 3 disentangled turtles were equipped with a combination of Wildlife Computers survivorship pop-up archival (sPAT) and SPLASH10-F-294D satellite tags, and Innovasea Systems V16-4H acoustic transmitters (K. L. Dodge et al. unpubl. data). We also obtained opportunistic, short-term (days to weeks) and long-term (8 yr) post-release outcome data from 6 turtles as a result of stranding or subsequent entanglement by using PIT

tag identification or cranial 'pink spot' photo ID to match individuals (McDonald & Dutton 1996).

3. RESULTS

3.1. Entanglement reports and response

The CCS hotline received 323 calls reporting a probable sea turtle entanglement over the 15 yr study period (2005–2019). Of those 323 reports, 280 were confirmed entanglement cases. We obtained a minimum of photo-documentation from 214 confirmed cases (76 %), including identification photos (e.g. pink spot; McDonald & Dutton 1996) for 92 individual leatherbacks. The most common reporting source was recreational boaters (62%), followed by commercial fishers (12%). The remaining reports came from a variety of sources, including ferries, charter vessels, beachgoers, aircraft, and federal, state, and municipal agencies. Only 7 confirmed entanglements involved cheloniid species, with 3 cases identified as loggerhead turtles, 2 cases as Kemp's ridley turtles, and 2 cases identified as small turtles with hard shells (unknown species). One turtle did not have enough descriptive information to determine if it was a leatherback or a cheloniid. Since the vast majority (97 %) of all confirmed entanglements involved leatherback turtles, our subsequent analyses will focus on the 272 leatherbacks reports.

Leatherback entanglement reports were primarily within Massachusetts jurisdiction off Cape Cod (CC), Massachusetts, in 3 broad geographic regions: north of CC (Cape Cod Bay/Massachusetts Bay); east of CC (Atlantic waters east of CC); and south of CC (Nantucket Sound, Vineyard Sound, Buzzards Bay) (Fig. 4). Almost all confirmed reports came from south (51 %) or north of CC (44 %), with relatively few reports east of CC (5 %). The percentage of live vs. dead leatherbacks varied by region, with a higher percentage of dead leatherbacks reported south (27 %, $n = 137$) and east (31 %, $n = 13$), compared with north of CC (5 %, $n = 121$) (Fig. 4). The number of confirmed leatherback entanglements reported over the 15 yr study period showed high inter-annual variability ($CV = 66.5\%$), with an average ($\pm SD$) of 18 ± 12 reports yr^{-1} and a peak in reports between 2012 ($n = 34$) and 2013 ($n = 52$) (Fig. 5). There was no significant trend in observed entanglement cases over time ($\beta_1 = 0.563$; $p = 0.45$; $R^2 = 0.04$).

Entanglements were reported from May to November, with a peak in reports during the month of August (38 %) over all years (2005–2019). Most

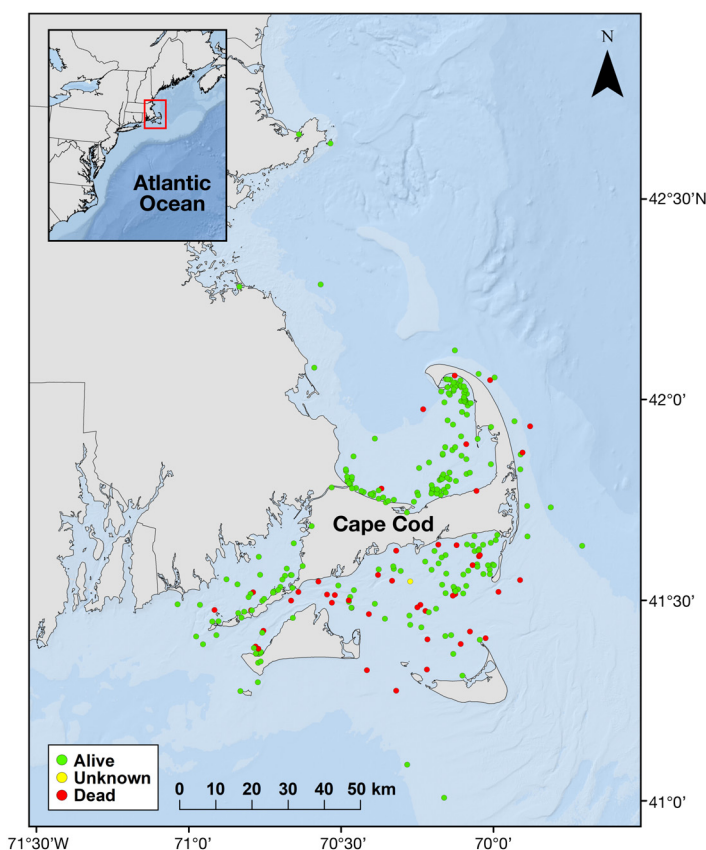


Fig. 4. Locations of 272 entangled leatherback turtles off Massachusetts, USA, 2005–2019

entangled leatherbacks were alive at the time of the first report (83 %). The percentage of live versus dead leatherbacks varied by month, with the highest number of mortalities in August, and an increasing proportion of dead leatherbacks as the season progressed. Of the 272 confirmed leatherback entanglements, 47 turtles were found dead in gear and 149 (55 %) were considered actionable, where the turtle was alive and accessible to responders. For actionable cases, 137 were freed and 11 were not relocated despite an extensive search. In 1 case, the turtle was unintentionally released with entangling gear after the line between the turtle and the boat parted. The remaining 76 cases were not considered actionable for various reasons: 51 cases were likely released by well-intentioned but untrained mariners prior to the responders' arrival ('ad hoc' disentanglement attempts with minimal data collection), of which only 19 had evidence to suggest they were fully disentangled. An additional 25 cases were reported during unfavorable conditions (lack of daylight, poor sea conditions, no RP standing by, or lack of trained personnel available). The 138 cases involving a trained

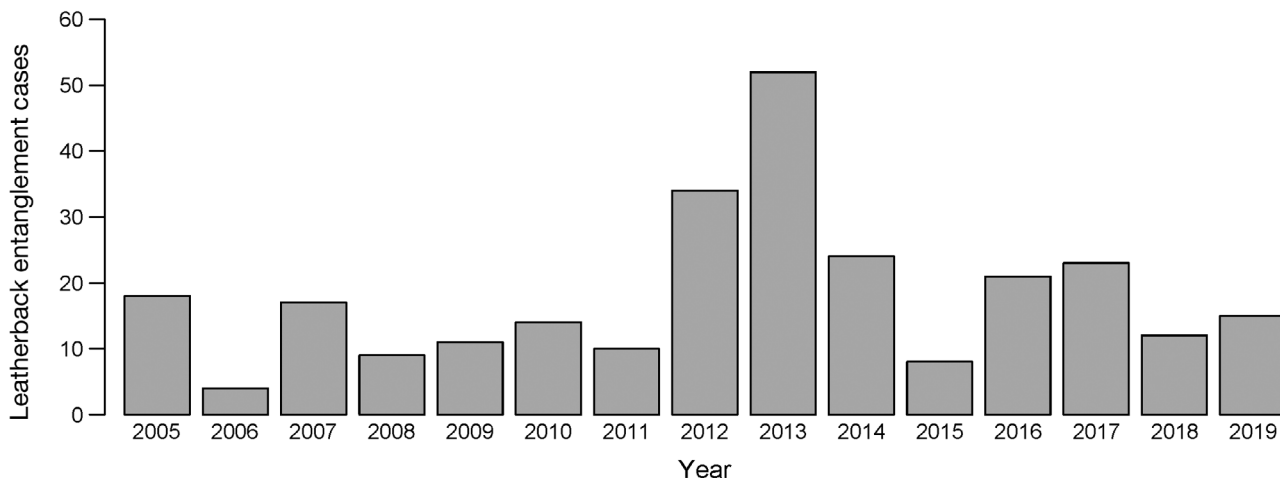


Fig. 5. Leatherback entanglement cases reported off Massachusetts, USA, by year, 2005–2019

MaSTDN responder produced much more detailed observations compared to cases that were simply confirmed reports or ad hoc attempts, with a much greater level of detail associated with MaSTDN responses. Of note, 137 out of 138 cases (99%) involving MaSTDN responders were released gear-free.

3.2. Turtle demographics

We collected morphometric data for 65 leatherback turtles in the field. Mean CCL was 149 cm (range: 116–169 cm). Thirty turtles (46%) were classified as adults (CCL ≥ 150 cm), 14 (22%) as subadults (≤ 140 cm), and 21 (32%) as unconfirmed age class ($140 \text{ cm} < \text{CCL} < 150 \text{ cm}$). For turtles classified as adults, we identified 9 (30%) females and 20 (67%) males, while 1 could not be sexed due to decomposition. Nine subadults were sexed through necropsy and veterinary examination, with a 1:2 female to male sex ratio (3 females, 6 males), consistent with the sex ratio of adult cases. We documented 3 individuals with Inconel flipper tags and traced 2 adult females to nesting beaches in Parismina (Costa Rica) and Trinidad, respectively, and 1 adult male to foraging grounds in Canada.

3.3. Gear type and characteristics

A buoy line of some type was identified in 251 out of 272 cases (92%). Entangling gear was inspected for its intended use in 185 cases, and the gear type was predominantly identified as pot/trap (92%), followed by moorings (3%), weir (2%), hook (1%),

research pot/trap (1%), and aquaculture (1%). The remaining cases ($n = 87$) involved gear, usually a buoy line (a buoy and rope), that could not be traced back to trap type. For the pot/trap gear entanglements, all leatherbacks were entangled in the buoy line, including a small number of cases (3%) that involved a surface system (i.e. highflyer and pick up buoy) (Fig. 1). Additionally, in 28% of pot/trap cases, the entangled turtle had swum into other gear, impinging its initial entanglement on 1 or more additional gear sets (Fig. 2A). We had no reports or observations of leatherbacks entangled in the weighted gear (pot/trap) or in the horizontal line (i.e. ground-line) between the traps of a trawl (Fig. 1). In 37% of all pot/trap gear entanglements ($n = 63$), we were able to determine if the pots were singles (84%) or part of a multi-pot trawl (16%). We identified the specific fishery associated with the entangling gear for 146 cases from registration numbers or hauling the entangling gear. The majority of cases north of CC (96%) involved buoy lines set on lobster traps, and cases south of CC (74%) involved buoy lines associated with traps set primarily for whelk and fish. For entanglement cases identified to fishery, commercial licenses were associated with 94%, while recreational licenses were associated with the remaining 6%. We made an increasing effort in later years of the study to haul and directly inspect gear. The characteristics of the entangling gear are described in Table 1.

We examined buoys associated with pot/trap entanglement of live turtles using our biofouling threshold. Of the 126 cases with sufficient documentation to assess biofouling, we found that only 4% met the criteria of possible marine debris/lost gear, while the

Table 1. Cases of leatherback turtles entangled in pot/trap gear and line only were used for analysis. The line color, estimated diameter, estimated material, and buoy type were based on images or responders in the field. More than 1 buoy could be associated with a given case. Buoy nose color was based on images. Only the buoy nose color was considered, as it was the portion most likely seen by the turtle

Gear characteristic	Entanglements	Percentage (%)
Buoy line color		
White	110	68
Green	23	14
Woven ^a	17	11
Blue	7	4
Black	2	1
Orange	2	1
Estimated buoy line diameter		
0.64 cm (1/4")	8	5
0.79 cm (5/16")	2	1
0.95 cm (3/8")	151	94
Estimated buoy line material		
Polyblend	138	86
Nylon	17	11
Cotton	4	2
Poly spliced to other	2	1
Buoy type		
Bullet with stick	90	41
Bullet	69	31
Acorn with stick	24	11
Stacked ^b	19	8.5
Acorn	6	3
Hardshell low drag	5	2
Surface system	5	2
Hardshell ball	2	1
Polyform	1	0.5
Buoy nose color		
White	62	31
Black	13	7
Other ^c	122	62

^aA 50/50 mix of strand colors. For all others, the dominant color was chosen and colored tracers were ignored
^bMultiple buoys of any type on the same stick
^cAny color that is not black or white, including multi-colored

vast majority of entanglements were associated with actively fished gear. Furthermore, 40% of the buoys that qualified as potential debris based on biofouling had current year trap tags. Given that leatherback turtles occur in areas where gear modifications for large whales are required (322 Code of Massachusetts Regulations 12.00, 50 Code of Federal Regulations Section 229.32), we also assessed 2014–2019 cases for presence of those modifications. We chose this time period because it was representative of multiple gear modifications for whale requirements and had thorough documentation. We assessed 49 cases

during this time period, all of which had either weak links or line markings (three 12-inch [~30 cm] colored marks on the buoy line denoting area fished). The vast majority of cases exhibited both weak links and line markings. None of the weak links that we examined were triggered or broken (Figs. 1 & 2B).

3.4. Entanglement characteristics, injuries, and post-release outcome

We were able to assess the impact of entanglement on turtle mobility for 170 cases. The majority of these entangled turtles were effectively anchored by the weighted gear (91%) (Fig. 2C), while the remainder were dead and drifting (5%) or alive but dragging entangling gear (4%). Of the turtles dragging gear, 3 displaced entire gear sets over long distances. Two turtles carried a single pot/trap a minimum of 24 and 48 km, respectively, and 1 turtle carried 2 single pot/trap sets a minimum of 4 km. The entanglement configuration was determined for 151 cases, and always involved wrapping line on the neck and/or front flippers (Fig. 2C), with a small number of cases involving additional body parts (e.g. rear flippers, carapace) (Fig. 6). Nearly all turtles (96%) were found entangled in the buoy line within 2 body lengths of the surface buoy, but we documented at least 5 cases with turtles entangled lower down on the buoy line. In these cases, the position of the turtles along the buoy line

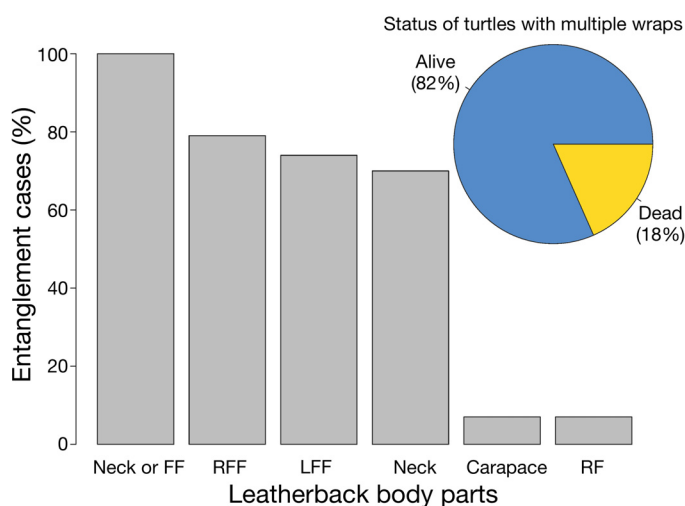


Fig. 6. Entanglement configuration relative to leatherback body parts, including cases with single and multiple wraps ($n = 151$ cases). Configuration typically involved the front flippers with at least 1 wrap of the neck or front flipper observed in all assessed cases. FF: front flipper; RFF (LFF): right (left) front flipper; RF: rear flipper. Inset: status of turtles with multiple wraps on any body part ($n = 98$ cases)

varied from 2 m above the pot/trap on the seafloor, to 4 m below the surface buoy. In addition to their primary entanglement in buoy lines, 4 turtles also had hooks and monofilament that were associated with the mouth, embedded, or wrapping a body part.

Using the NMFS post-interaction mortality criteria for 88 cases, we categorized the risk of post-release mortality as low (60% Category 1), intermediate (32% Category 2), or high (8% Category 3). We had 100% agreement in category assignment with the 9 cases previously assessed by NMFS (Upite et al. 2019). All cases had some level of visible injuries from their entanglements, including scuffing, abrasions, or bleeding associated with at least one body area, and almost all cases (95%) had injuries on the carapace, primarily near the neck and flipper insertions (Fig. 2D). Most injuries (82%) were associated with wrapping rope.

We obtained post-release outcome data for 16 turtles from electronic tags, strandings, and subsequent entanglements (Table 2). Three turtles died within weeks of disentanglement, including 2 turtles with electronic tags and one stranding. Necropsies of the tagged turtles showed that one drowned from a sec-

ond entanglement after 19 d of tracking (Fig. 2E), and one died after 34 d of tracking, having been entangled at least twice within 11 d, and having ingested a large sheet of plastic (83.5 × 35 cm). One stranded turtle was found dead 39 d post-release, with the time of death unknown. A second stranded turtle was identified via PIT tag, confirming over 8 yr of post-release survival after its second disentanglement. Post-release outcome was inferred from electronic tags for 8 other individuals, with tracking durations that ranged from 16 to 261 d. Two out of the 8 tagged turtles stopped transmitting prematurely at 16 and 34 d, respectively, but mortality could not be determined from the MK10 tag model. Of the remaining 6 tagged turtles, one was tracked with a sPAT that indicated survival after 30 d, and 5 turtles were tracked long-term with acoustic or MK10 tags for 182 to 261 d. Six turtles were documented as alive during subsequent entanglement events that occurred 2 to 11 d after initial disentanglement. In total, we documented 7 individuals that were entangled at least twice within a single season. When we compared our NMFS categorizations with post-release outcome data, there was generally good agreement between predicted and

observed outcome (Table 2). The predictions would have resulted in 2 deaths, and in reality resulted in 1 confirmed death. The second predicted death was more difficult to interpret since the turtle's tag stopped transmitting after 16 d, but provided no definitive mortality data. The majority of disentangled turtles (88%) were predicted to have a low or intermediate risk of mortality, while our post-release outcome data showed that 78% of turtles survived from 2 to almost 3000 d.

4. DISCUSSION

Over the past decade, leatherback nest numbers have declined across the majority of monitored nesting beaches within the Northwest Atlantic (Northwest Atlantic Leatherback Working Group 2018), resulting in an IUCN Red List status upgrade to Endangered for the Northwest Atlantic subpopulation (Northwest Atlantic Leatherback Working Group 2019). To explain these declining

Table 2. Post-release monitoring outcome for 16 individual leatherbacks, from 2005 to 2019. Entanglement refers to a turtle that was observed during a second entanglement event (serial entanglement). sPAT: survivorship pop-up tag. NMFS Category refers to the post-release risk of mortality defined by NMFS criteria: low (Category 1, 10% risk), intermediate (Category 2, 50% risk), and high (Category 3, 80% risk). The NMFS Category refers to the prediction from the previous entanglement event. Tagged turtles were assumed to be alive at the time of last transmission

Turtle ID	Monitoring method	Duration (d)	Turtle outcome	NMFS Category	Source
TD05-F	Entanglement	4	Alive	2	This study
TD07-10	SPLASH tag	34	Alive	1	Dodge et al. (2014)
TD07-12	SPLASH tag	19	Dead	1	Dodge et al. (2014)
TD07-13	SPLASH tag	16	Alive	3	Dodge et al. (2014)
TD07-16 ^a	Entanglement	11	Alive	1	This study
TD07-18 ^a	SPLASH tag	34	Dead	2	Dodge et al. (2014)
TD07-17	SPLASH tag	182	Alive	1	Dodge et al. (2014)
TD08-07	SPLASH tag	234	Alive	1	Dodge et al. (2014)
TD09-09	SPLASH tag	203	Alive	1	Dodge et al. (2014)
TD12-28	Entanglement	2	Alive	2	This study
TD13-18 ^b	Entanglement	3	Alive	1	This study
TD13-29 ^b	Stranding	2972	Dead	2	This study
TD14-19	Stranding	39	Dead	3	This study
TD17-08	Entanglement	2	Alive	2	This study
TD18-08	Entanglement	7	Alive	2	This study
TD19-01	Acoustic tag	261	Alive	1	This study
TD19-10	SPLASH tag	218	Alive	2	This study
TD19-11	sPAT	30	Alive	1	This study

^aTD07-16 and TD07-18 are the same individual
^bTD13-18 and TD13-29 are the same individual

trends, one hypothesis points to a potential increase in the number of lethal leatherback–fisheries interactions (Northwest Atlantic Leatherback Working Group 2018). Much attention and resource allocation has historically focused on bycatch in some fishing gear types, primarily large-scale, industrial fisheries like pelagic longlines, with some positive progress on bycatch mitigation for leatherbacks and other sea turtle species (Gilman 2011, Swimmer et al. 2017). Other types of fisheries (coastal gillnets, artisanal longlines, pots/traps) have been increasingly identified as a significant global threat to leatherback turtles in coastal foraging, migration, and breeding areas (James et al. 2005, Lee Lum 2006, Alfaro-Shigueto et al. 2007, 2011, López-Mendilaharsu et al. 2009, Hamelin et al. 2017, Ortiz-Alvarez et al. 2020). Bycatch in small-scale, coastal gillnet fisheries near nesting beaches in Trinidad and the Guianas has been estimated at 1000–3000 leatherbacks yr^{-1} (Laurent et al. 1999, Eckert & Eckert 2005, Lee Lum 2006, Eckert 2013). These high bycatch levels have been implicated as a major driver in the decline of the Northwest Atlantic leatherback population (Lee Lum 2006, Eckert 2013, Northwest Atlantic Leatherback Working Group 2018, World Wildlife Fund – Guianas 2019). Leatherback bycatch in pot/trap fisheries is less well understood but is routinely reported in Atlantic Canada (Hamelin et al. 2017) and US waters. The infrastructure provided by the disentanglement network in Massachusetts, supported by state and federal government agencies, provides an alternative means of collecting bycatch data in fisheries where the gear is passively fished and a traditional observer program is challenging.

In Massachusetts, opportunistic entanglement reports largely come from recreational boaters. The peak of recreational boating occurs during boreal summer, which is also the peak co-occurrence period for leatherbacks and fixed-fishing gear. Recreational boaters account for the majority of vessels in Massachusetts, likely contributing to the high number of opportunistic reports from this group. Direct solicitation of reports from commercial fishers via dockside interviews, surveys, and reporting hotlines has been successfully used to assess fishery bycatch elsewhere (Martin & James 2005, Lee Lum 2006, Peckham et al. 2007, Moore et al. 2010, Alfaro-Shigueto et al. 2018, Ortiz-Alvarez et al. 2020). In Atlantic Canada, just north of our study area, over 70% of the entanglement reports come from commercial fishers (Martin & James 2005, Hamelin et al. 2017). Commercial fishers in New England have been the subject of individual lawsuits over entanglements, as well as evolving

state and federal regulations and closures that limit access to fishing grounds. For these reasons, they may currently be reluctant to report entanglements of marine megafauna, as evidenced by the small percentage (12%) of leatherback reports we received from commercial fishers. Commercial fishers also account for fewer vessels in Massachusetts, and therefore fewer eyes on the water, which may also contribute to their relatively low reporting numbers compared to other sources. With this in mind, increased outreach effort should be made to encourage entanglement reporting from the fishing community.

The size demographics of entangled turtles in our sample mirror those from direct capture research and strandings in Massachusetts (Dodge et al. 2014, K. Sampson unpubl.). Adult sex ratios were similar between entanglements and direct capture research (Dodge et al. 2014) with more males than females, but differed from local strandings based on data from 51 turtles, assessed from 2010 to present, where females (57%) outnumbered males (43%) (K. Sampson unpubl.). While identification tags were present for only a handful of individuals, complementary genetics data confirm that the source nesting populations for most Massachusetts leatherbacks (stranded, entangled, and live captures) are from Trinidad/French Guiana and Costa Rica (Roden et al. 2017, K. Stewart & P. Dutton unpubl. data). This is consistent with the genetic composition of foraging leatherbacks off Atlantic Canada (Stewart et al. 2013), and bycaught turtles in the US Atlantic pelagic longline fishery (Stewart et al. 2016). While these source populations are the largest in the Northwest Atlantic, their stock-level trends are declining (Northwest Atlantic Leatherback Working Group 2018).

For cases where gear could be identified to target species, most leatherback turtles were entangled in actively fished (as opposed to lost or abandoned traps), commercial lobster gear, specifically the buoy lines of single traps, with a negligible number of cases associated with purported marine debris. Almost half of the ‘debris’ cases had current-year trap tags, highlighting the difficulty of distinguishing active fixed-gear fisheries from marine debris (Asmutis-Silvia et al. 2017). A wide variety of buoy and line styles/colors were observed, and although we do not know the proportion of styles/colors available, the diversity in our data suggests that these characteristics had no obvious effect on the risk of entanglement. Surface buoys have been hypothesized to be a jellyfish mimic and potential attractant for foraging leatherbacks (Lazell 1976), and loggerhead turtles are known to forage on buoys associated with floating

debris and fish aggregating devices (Blasi et al. 2016, Fukuoka et al. 2016). However, we found no evidence of bite marks when buoys were examined, and we did not observe jellyfish aggregated near buoys during disentanglement operations.

Buoy lines are similar across different pot/trap fisheries in both materials and configuration in the water column, and all pot/trap fisheries (lobster/whelk/fish) are active during the summer and fall foraging season of leatherbacks. For entangling gear that was identified north of CC (primarily Cape Cod Bay), most was lobster gear and the remainder was whelk or fish gear. Conversely, entangling gear identified south of CC was mostly whelk and fish gear, and the remainder was lobster gear. The entanglements reflect the prevalent gear types that occur north (lobster) and south (whelk, fish) of CC (E. Burke pers. comm), and the turtles appear to get entangled in the gear type that is most common in the region. Mortalities were 6 times higher to the south of CC than to the north, driven by high numbers of entangled carcasses in 2012. However, even excluding 2012, leatherback mortalities were 3 times higher to the south. The difference in observed mortalities between regions is surprising, considering that multiple factors (e.g. fishery season, buoy line construction, fishing depth, ad hoc disentanglement rates, reporting sources) are comparable across regions. Future work should address other potential explanatory variables such as regional differences in fine-scale temperature, turtle behavior patterns, and fishing practices (e.g. trap-haul frequency) during peak turtle presence, and the region south of CC should be considered a high priority for mitigation strategies.

Leatherback turtles in this study were mostly reported entangled near the surface, similar to what was found in Atlantic Canada (Hamelin et al. 2017). Entanglement reports in our study were necessarily biased towards the surface portions of gear where turtles could be seen, since most observations came from sources other than fishers. Only commercial fishers would have access to the entire gear set during hauling. However, in 2 entanglement cases reported off Rhode Island and New Jersey, leatherbacks were entangled at depth (15 m) and in groundline between weighted traps, respectively (K. Sampson unpubl.), indicating that entanglement can occur anywhere in the water column. Massachusetts banned the use of floating groundline between traps starting in 2007 to mitigate whale entanglements, reducing the amount of line in the water column and likely providing benefit to sea turtles. Since we are documenting entanglements after they occur, we do

not know where the turtle originally contacted the line, as they could slide up or down the line after contact and before the line becomes wrapped around the neck and/or flipper(s), so the distance between the buoy and the turtle should be interpreted with caution. In the field, we have released turtles and felt them swim back into the line that we were still holding, pushing against it and moving up and down the line until they moved off it. Footage of a leatherback interacting with a buoy line in Martinique also demonstrates that leatherbacks can move up and down the line after first contact, before wraps occur (<https://www.youtube.com/watch?v=q4Qyg1pzUTo>). Furthermore, in at least 1 of the 3 cases in which turtles dragged gear over significant distances, the turtle moved into water deeper than the length of the buoy line. This case highlights the potential for turtles to drown at depth, where they will not be detected, and for gear to be transported beyond where it was originally set.

Entanglement data came from opportunistic reports rather than systematic surveys, and entanglement events are likely underreported. This precludes our ability to quantify leatherback bycatch rates, or to estimate bycatch for the entire region's fisheries. While we cannot directly compare estimated bycatch rates for pot/trap fisheries with estimates for other fisheries, we can compare directly observed bycatch numbers. Observed sea turtle bycatch in gillnet, longline, and trawl fisheries worldwide from 1990 to 2008 was about 85 000 turtles, although the authors considered this a gross underestimate (Wallace et al. 2010). Specific to leatherback turtles in the North Atlantic, Swimmer et al. (2017) reported 844 observed captures in US longline fisheries from 1992 to 2015. In fixed-gear fisheries off Atlantic Canada, 205 leatherback bycatch events were recorded from 1998 to 2014 (Hamelin et al. 2017). While the number of by-caught leatherbacks reported in our study is small in the context of global bycatch, our numbers are comparable to observed captures in Canadian fixed-gear fisheries and the US Atlantic longline fishery. Since data collection methods varied between countries and regions, these comparisons should be interpreted with caution. It is also important to consider that entanglement in fixed gear is just one of multiple, cumulative, bycatch threats faced by leatherback sea turtles during annual migrations between breeding and foraging grounds in the North Atlantic (Lee Lum 2006, Fossette et al. 2014, Stewart et al. 2016). In high-quality, localized foraging areas like Atlantic Canada (James et al. 2005) and New England (Dodge et al. 2014), where leatherbacks accumulate energy

stores for breeding and migration, reducing fisheries threats is critical for population stability and growth (Wallace et al. 2018).

Most entangled leatherbacks were alive at the time of first reporting, and NMFS post-interaction mortality criteria predictions indicated that most turtles had a low to intermediate risk of mortality. Post-release monitoring also indicates that most turtles survived in the days to months following disentanglement; however, post-release monitoring was done for <7% of the entanglement cases reported in this study. Since entanglement produces a spectrum of physical injuries and physiological effects (Innis et al. 2010, Hunt et al. 2016), turtles that are released alive may die in the days to weeks following disentanglement. NMFS post-interaction mortality criteria predictions, when compared to cases with post-release outcome data, suggest that the NMFS technique can be used to predict turtle outcome with some degree of accuracy in the absence of monitoring data, but our validation sample was small at only 17 cases. We also documented 7 cases of serial entanglement, with turtles becoming entangled at least twice within days to weeks. The original entanglement wounds, often considered minor lesions, looked more severe at the time of the second disentanglement event. This may be due to pressure necrosis from constricting lines, similar to chronic entanglement injuries documented in cetaceans and pinnipeds (Moore et al. 2013) (Fig. 2E). In addition to serial entanglements over these longer time periods, we also documented 2 cases in 2019 of confirmed immediate re-entanglements, whereby a turtle was disentangled and then became entangled in a nearby gear set as soon as it was released. A third case of immediate re-entanglement and mortality was inferred from tag data. Given the unique circumstances of these events, they were not included in the overall entanglement case numbers but highlight the need for post-release monitoring.

Animals that survive a fishery interaction can experience acute and/or delayed sublethal effects. These may involve physical injury, physiological derangements, reflex impairment, behavioral changes, and energetic costs, with potential impacts to their fitness including growth, reproductive output, and predator avoidance (reviewed by Wilson et al. 2014). The frequency of leatherback serial entanglements is unknown, but cumulative impacts of multiple entanglements in other taxa can lead to stunted growth (Stewart et al. 2021), and may result in a greater risk of mortality and morbidity (Robbins et al. 2015). Our documentation of hook and line, in addition to buoy line interactions, shows that leatherback turtles face

multiple, overlapping fisheries threats. Scar studies and post-release monitoring with electronic tags have demonstrated that some leatherbacks can recover from entanglement injuries and resume normal behaviors (López-Mendilaharsu et al. 2009, Innis et al. 2010, Dodge et al. 2014, Archibald & James 2018), but turtle outcome has been documented for very few cases. Observations from this study support the development of scar-based studies using a pattern of wrapping injuries to monitor the extent of entanglement in free-ranging populations. Increasing post-release monitoring efforts is imperative to understand true leatherback mortality rates associated with pot/trap entanglements.

Current federal and state gear-modification measures for buoy lines in New England's fixed-gear fisheries (i.e. weak rope, weak links) were developed to mitigate large whale entanglements, and have no apparent benefit to leatherback turtles. The breaking strength of weak ropes at 1700 pound-force (lbf; 0.771 ton-force metric) is geared towards right whales (Knowlton et al. 2016) and is too high to release leatherbacks, and we found unbroken/untriggered weak links, intended to break at <600 lbf, in almost all well-documented entanglement cases. Temporal mitigation measures (e.g. seasonal closures) for right whales will also not help leatherback turtles since these species occupy Massachusetts waters during opposite seasons, with right whales mostly present during winter/spring (Davis et al. 2017), and leatherbacks present in summer/fall (Dodge et al. 2014). Since line in the water column presents a risk, regardless of origin (e.g. fishery, mooring, aquaculture), any activity that introduces more line can exacerbate the entanglement problem. Even tensioned line, such as a mooring line attached to a vessel (observed in a case from 2005) or chain (observed in a case from 2019, see Fig. 2F) can create an entanglement hazard. Tensioned line and weak links have been suggested as entanglement mitigation measures for aquaculture installations, but these may be ineffective for sea turtles in their current iterations. Aquaculture has steadily increased over the past 20 yr, and offshore marine aquaculture is poised to undergo rapid expansion (Naylor et al. 2021), with the potential to introduce thousands of new vertical and horizontal lines into the Northwest Atlantic (Price et al. 2017). Seasonal mismatch, as is the case for cold-water kelp farming in New England during boreal fall and winter (Grebe et al. 2019), will minimize risk to sea turtles, but we need novel approaches to address entanglement risk associated with longline shellfish aquaculture (Price et al. 2017).

Since line in the water column creates risk, any meaningful reduction in the amount of line should help leatherback turtles. Both single sets (a pot with 1 buoy line) and trawls (multiple pots strung together and marked with 1 or 2 buoy lines) produce comparable risk of injury and mortality, so reducing single sets in favor of trawls could minimize overall risk by decreasing the number of buoy lines in leatherback habitats. Managers should focus on strategies to reduce the co-occurrence of sea turtles and fixed-fishing gear by using all methods at their disposal, including reductions in the number of buoy lines allowed, seasonal and area closures targeted to reduce sea turtle–gear interaction, and the development of emerging technologies such as ‘ropeless’ fishing (Myers et al. 2019). As we work towards effective bycatch mitigation for leatherback turtles in pot/trap fisheries, maintaining a trained and active disentanglement network is paramount. Based on data from strandings and chronic entanglements, leatherback turtles do not appear able to shed wrapped lines on their own, and require intervention to free them from fishing gear. Without disentanglement, every interaction described in this study would be considered a lethal take.

This study creates a baseline to measure entanglement mitigation efforts that could be replicated in other areas with similar conditions but limited infrastructure. Entanglement responders collected detailed data about the turtles and entanglement events that offer unparalleled insight into the problem of entanglement, in contrast to low-quality or no documentation from untrained reporting parties or ‘ad hoc’ disentanglement attempts. In the near-term, we recommend sustaining disentanglement network activities, increasing fisher participation in research activities and post-release monitoring efforts, and analyzing data on fishing effort relative to entanglement. Long-term goals should include quantifying bycatch and implementing effective mitigation through line reductions, buoy line modifications geared towards sea turtles, and careful consideration of spatio-temporal permitting of any new lines (e.g. aquaculture farms) in sea turtle habitats.

Acknowledgements. We thank all past and present members of the Marine Animal Entanglement Response (MAER) team and the Atlantic Large Whale Disentanglement Network. Special thanks to the US Coast Guard, Mass Environmental Police, municipal harbor masters, and fishing partners who supported entanglement response efforts. For tagging support, we thank the Large Pelagics Research Center, New England Aquarium Rescue and Animal Health Departments, Northeast Fisheries Science Center, Coon-

amasset Farm Foundation, M. Dodge, G. Purmont, M. Leach, E. Eldredge, S. Eldredge, R. Martin, S. Leach, J. Wilson, M. Murphy, and G. Tomasian. We thank R. Knotek for assistance with Fig. 4, and J. Robbins, N. Whitney, C. Upite, B. Wallace, J. Senko, and 1 anonymous reviewer for helpful suggestions. We thank Massachusetts Division of Marine Fisheries for sharing fisheries data and comments that improved the manuscript. Tag recovery data for TD13-29 was provided by the Atlantic Marine Conservation Society and Archie Carr Center for Sea Turtle Research. CCS disentanglement work is supported by a grant from the National Oceanic and Atmospheric Administration (NOAA), the Massachusetts Division of Marine Fisheries (MA-DMF), and the Massachusetts Environmental Trust. Support for the MAER team also comes from the Grace W. Allsop Foundation, DJ & T Foundation, Max and Victoria Dreyfus Foundation, Mary P. Dolciani Halloran Foundation, Hermann Foundation, Island Foundation, MALLRD Foundation, Pegasus Foundation, Towle Ocean Conservation Foundation, Alexandra Rose Tozzi Memorial Foundation, G. Unger Vetlesen Foundation, and contributions from CCS members. Funding for post-release monitoring was provided by Massachusetts Environmental Trust Grant #CT ENV MET2019NEAQUARIUM, NOAA Grant #NA04NMF4550391, National Fish and Wildlife Foundation Grant #2008-0076-000, and the Cape Cod Commercial Fisherman’s Alliance. K.L.D. was partially supported by NOAA Grant #NA17OAR4170297. Tagging work was conducted under the authority of NMFS Permit No. 1557-03 and 21301, University of New Hampshire IACUC #060501 and 090402, and New England Aquarium IACUC #06-03, 2013-07, 2016-03, and 2019-03. Photos courtesy of Sean Whelan/Woods Hole Oceanographic Institution (Fig. 2C) and Mass Audubon’s Wellfleet Bay Wildlife Sanctuary (Fig. 2F).

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Editorial responsibility: Bryan P. Wallace,
Fort Collins, Colorado, USA

Reviewed by: J. Senko and 1 anonymous referee

Submitted: September 21, 2021

Accepted: December 3, 2021

Proofs received from author(s): February 9, 2022