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RESEARCH ARTICLE

Incidental capture of leatherback sea turtles in fixed fishing gear off Atlantic Canada

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Abstract

1. Incidental capture in commercial fishing gear is a threat to many populations of marine megafauna, including sea turtles. While research has largely focused on pelagic longline impacts on sea turtles, fixed-gear fisheries are a significant, historically understudied source of injury and mortality.
2. The present study assesses the interaction of endangered leatherback sea turtles (*Dermochelys coriacea*) with fixed-gear fisheries in high-latitude seasonal foraging habitat where sub-adult and adult turtles aggregate.
3. Records of leatherback-fishery interactions (n = 205) were compiled from databases of publicly-reported sea turtle sightings in Atlantic Canada (1998–2014) to identify the spatio-temporal distribution of these events; to identify corresponding fisheries and gear types; and to describe the mechanics and outcomes of entanglements in fixed gear.
4. Most reports came from coastal Nova Scotia (n = 136) and Newfoundland (n = 40), with reporting rates peaking in the mid-to-late 2000s. The majority of entanglements were reported during the summer months of July and August when leatherbacks are seasonally resident and several fisheries are active in continental shelf waters.
5. Entanglements were most commonly reported in pot gear (e.g. snow crab, lobster, whelk) and trap nets (e.g. mackerel), reflecting extensive use of polypropylene lines distributed in the upper water column where leatherback foraging activity is concentrated.
6. Given reporting biases and uncertainty regarding post-release survivorship, entanglement mortalities should be considered a gross underestimate of true mortality rates.
7. This study highlights both the importance of looking beyond pelagic longlines to evaluate leatherback interactions with fixed-gear fisheries in high-use continental shelf foraging habitat, and of involving the fishing industry in developing mitigation measures to reduce entanglement rates and associated turtle mortality.

KEYWORDS

coastal, distribution, endangered species, fishing, ocean, reptiles

1 | INTRODUCTION

Incidental capture in commercial fishing gear has been identified as a leading cause of anthropogenic mortality for many species of marine animals worldwide, including sea turtles (Lewison, Crowder, Read, & Freeman, 2004; Wallace, Kot, & DiMatteo, 2013), sharks (Baum et al., 2003), seabirds (Anderson et al., 2011), and marine mammals (Read, Drinker, & Northridge, 2006). The population-level implications of bycatch are especially serious for species which are slow to mature and long-lived, making them vulnerable to even low levels of adult mortality (Heppell, Heppell, Read, & Crowder, 2005; Lewison, Crowder et al., 2004). As a result, fisheries entanglement has been studied extensively as a primary cause of population decline for critically endangered species such as the North Atlantic right whale *(Eubalaena glacialis*) and other large baleen whales (Johnson et al., 2005; Knowlton & Kraus, 2001; Kraus et al., 2005). Incidental capture, including hooking, net entrapment, and entanglement in fishing gear, is also considered a major cause of population decline for adult and sub-adult sea turtles (FAO Fisheries and Aquaculture Department, 2010; Hamann et al., 2010; Lewison & Crowder, 2007; Wallace et al., 2013), including the endangered leatherback sea turtle (*Dermochelys coriacea*) (SARA, 2002).

The leatherback turtle is a widely distributed marine reptile that undertakes long-distance migrations between feeding and breeding areas (Eckert et al., 2006; James, Sherrill-Mix, Martin, & Myers, 2006). Leatherbacks have been reported interacting with a broad suite of fisheries operating in oceanic and coastal areas, both in their foraging zones (Alfaro-Shigueto, Dutton, Van Bressem, & Mangel, 2007; Fiedler et al., 2012; James, Myers, & Ottensmeyer, 2005; Vélez-Rubio, Estrades, Fallabrino, & Tomás, 2013) and in waters adjacent to nesting beaches (Gilman et al., 2010; Lee Lum, 2006). To date, the majority of leatherback entanglements documented globally, and particularly in high-latitude waters like the temperate Northwest Atlantic, involve interactions with large pelagic longline fisheries. Pelagic longline fisheries, which operate worldwide, are of high economic value and are overseen by regional fisheries management organizations as well as by national and international management authorities, all with relatively stringent bycatch monitoring and reporting requirements (Cox et al., 2007; Fossette et al., 2014; Roe et al., 2014). Bycatch levels in this fishery are also subject to a relatively high degree of scrutiny by academia, industry, and non-governmental organizations.

While pelagic longline fisheries pose a threat to leatherbacks during their trans-oceanic pelagic migrations and in offshore foraging areas, aerial and telemetry data from foraging leatherbacks in temperate and boreal waters of the Northwest Atlantic attest to relatively high concentrations of these turtles on the continental shelf (Dodge, Galuardi, Miller, & Lutcavage, 2014; James et al., 2006; James, Ottensmeyer, & Myers, 2005; Shoop & Kenney, 1992) where fixed fishing gear is broadly distributed. In Atlantic Canadian waters, leatherbacks arrive during late spring and summer to feed on seasonally abundant jellyfish, notably *Cyanea capillata* (Heaslip, Iverson, Bowen, & James, 2012; James & Herman, 2001; Wallace, Zolkewitz, & James, 2015). The turtles depart for breeding areas and southern oceanic foraging areas in autumn (James et al., 2006). Atlantic Canada hosts one of the largest seasonal foraging aggregations of adult and sub-adult leatherbacks in the Northwest Atlantic (James et al., 2006), representing turtles from nesting populations throughout Central and South America, the United States, and the Caribbean (Stewart, James, Roden, & Dutton, 2013). As such, Canadian waters are particularly significant to the future of endangered leatherback turtles in the Atlantic, and portions of this region have been proposed as critical habitat for the species under Canada's Species at Risk Act (DFO, 2012a).

Studies have suggested that there is a higher risk of entanglement and higher mortality rates associated with leatherback turtle bycatch in fishing gear that is anchored to the ocean bottom (henceforth referred to as ‘fixed gear'), compared with bycatch in pelagic longline gear in the temperate Northwest Atlantic (James, Ottensmeyer et al., 2005; Wallace et al., 2013). The period during which leatherbacks are resident in continental shelf waters of Atlantic Canada coincides with open seasons for various time-managed commercial fixed-gear fisheries. Analogous to the rationale behind management steps taken to help recover large whale species in the temperate Northwest Atlantic (Brown et al., 2009; Read et al., 2006), there is evidence that adult leatherback mortality at temperate and boreal high-latitude foraging grounds might be most effectively reduced through entanglement mitigation focused on fixed gear (James, Ottensmeyer et al., 2005). However, a first priority is to better understand leatherback–fishery interactions in this area.

There remains a paucity of published information on incidental capture of leatherbacks in north-eastern USA and Atlantic Canadian waters. Only small numbers of entanglements from Canada have previously been summarized (Bleakney, 1965; Goff & Lien, 1988). James, Ottensmeyer et al. (2005) reported that leatherbacks in Atlantic Canada are regularly caught in buoy lines, citing an additional 83 records, but providing few details.

Building upon this evidence, the present study represents the first comprehensive, quantitative assessment of leatherback turtle–fishery interactions in Atlantic Canada. Many studies evaluating the entanglement risk of sea turtles rely on data derived from fishery observer programmes (Lewison, Crowder et al., 2004; Lewison & Crowder, 2007) or animal stranding networks (Adimey et al., 2014; Barrios-Garrido & Montiel-Villalobos, 2016; Vélez-Rubio et al., 2013). Fishery observer programmes are costly to implement and rarely provide representative sampling effort, particularly for fixed-gear fisheries (Lewison, Crowder et al., 2004). Animal stranding networks rely on inferences made primarily from dead animals that have washed ashore, representing only a subset of all animals that interact with gear, and from which the origin of injuries is not always clear (Barrios-Garrido & Montiel-Villalobos, 2016; Casale et al., 2010; Vélez-Rubio et al., 2013). In contrast, this study includes data reported by fishers, mariners, and other coastal community members directly to regional not-for-profit marine animal research and conservation organizations, as well as data collected during seasonal field research in Canadian waters.

The present study describes spatio-temporal patterns in interactions between leatherbacks and fixed-gear fisheries operating in continental shelf waters off Atlantic Canada, identifies the types and components of fishing gear most commonly implicated in reported leatherback entanglements, describes the mechanics and outcomes of leatherback entanglements, identifies factors affecting entanglement reporting, and recommends potential measures to mitigate leatherback entanglement in fixed gear.

2 | METHODS

2.1 | Data compilation

Leatherback entanglement records from 1998 to 2014 were obtained by querying regional databases of leatherback turtle sightings maintained by the Canadian Sea Turtle Network (CSTN; formerly the Nova

Scotia Leatherback Turtle Working Group) and Whale Release and Strandings – Newfoundland and Labrador (WRS). Established in 1998, the CSTN is a Nova Scotia-based charitable organization dedicated to the study and conservation of sea turtles in Canadian waters and worldwide (Martin & James, 2005a, 2005b). WRS is a Newfoundland and Labrador-based marine animal release and strandings programme that has been responding to incidental entrapments, entanglements, and strandings in the province since 1978. This analysis considered only records since 1998, when the CSTN was established. Potential entanglement reporting areas corresponded to continental shelf waters of the Atlantic Canadian provinces (approximately 42–55° N, 50–70° W). This region encompasses the Bay of Fundy, Scotian Shelf, Cabot Strait, Gulf of St. Lawrence, and coastal Newfoundland and Labrador.

Entanglement records included turtles reported to the CSTN and WRS by fishers and members of the general public, turtles handled directly by the CSTN field team during research operations (1999–2014), and turtles reported to the CSTN or WRS via government agencies (e.g. Fisheries and Oceans Canada [DFO], Nova Scotia Department of Natural Resources) or other organizations (e.g. Marine Animal Response Society). Entangled leatherbacks were defined as turtles that were living or dead, and either entrapped or hooked in fishing gear, stranded on shore with gear attached, floating at sea with gear attached, or free-swimming and trailing gear. Turtles with injuries or scars suggestive of previous entanglement were only included if compelling evidence of the specific gear involved was present.

Data collected for each entanglement record included the date, time, and location of the entanglement event, as well as the sex of the turtle (if known) and the turtle condition (alive or dead – at sea, stranded, or entrapped). For those records only associated with descriptive locations, coordinates were geo-referenced as precisely as possible using Google Earth (https://www.google.com/earth/). There were also a number of records for which the location details were too vague to assign specific coordinates and these records were excluded from spatial analyses where appropriate. Similarly, records that did not have a specific date, but were substantiated with photographs or other information, were considered anecdotal and were excluded from temporal analyses where appropriate. To investigate sources of entanglement reporting, the types of reporters (e.g. fisher, fishery observer, etc.) were recorded.

2.2 | Data analysis

Analysis of turtle entanglement data was conducted using 'R' Statistical Computing Software (R Core Team, 2014). Results were reported as mean ± standard error, unless otherwise specified. The *maptools* (Bivand & Lewin-Koh, 2014), *rgdal* (Bivand, Keitt, & Rowlingson, 2014), and *GISTools* (Brunsdon & Chen, 2014) packages were used to map the spatial distribution of leatherback entanglements in Atlantic Canada.

Results were not weighted according to sighting effort, as there were no dedicated turtle surveys conducted except for those that took place as part of the CSTN-DFO annual in-water field research (Archibald & James, 2016), which did not specifically target entangled turtles. Sighting effort in this study was largely a function of fishing effort, but was also both opportunistic and dependent on members of the public responding to advertising campaigns. Records were not weighted according to changes in fishing practices or gear configurations over time because the goal of this study was to assess and document impacts as they occurred, regardless of subsequent changes within fisheries (consistent with Wallace et al., 2013).

3 | RESULTS

In total, 205 leatherback entanglements were reported in Atlantic Canada between 1998 and 2014. The sex of the turtle could be determined in 15.1% of cases (n = 31). There was no significant difference between the percentage of entangled turtles that were male (51.6%; n = 16) and the percentage that were female (48.4%; n = 15; p = 0.47, z-test).

3.1 | Temporal patterns

On average, 12.1 ± 1.56 entanglements were reported per year, with a maximum of 23 in 2005 and 21 reports in each of 2003 and 2008 (Figure 1). The number of entanglements reported per year was variable (coefficient of variation [CV] = 53.6%), but generally increased in frequency until the mid-to-late 2000s, after which the annual number of entanglement reports declined.

Leatherback entanglements were reported primarily between June and October, with most reported in July (n = 59; monthly average per year: 3.5 ± 0.60) and August (n = 50; monthly average per year: 2.9 ± 0.80; Figure 2). On rare occasions, entangled turtles were found in colder months. In the months of November through January, 1998–2014, there were 10 entangled leatherbacks reported.

3.2 | Geographic patterns

Reported entanglements were widely, but not uniformly, distributed throughout the region (n = 195; Figure 3). Most of the reports came from coastal Nova Scotia (n = 136), with a notable concentration of reports on the Atlantic coast, particularly in the vicinity of the city of Halifax, and around Cape Breton Island. There was a conspicuous concentration in the vicinity of the Canso Causeway, an embankment impermeable to marine animal passage that connects Cape Breton Island to mainland Nova Scotia. Newfoundland and Labrador was also the site of many entanglement incidents (n = 40), which were dispersed around the extensive coastline. The most northern record came from Labrador. There were also entanglement reports from the provinces of Prince Edward Island (n = 10), Québec (including the Magdalen Islands) (n = 3), and New Brunswick (n = 3). While outside the principal study area, three reports of entanglements from fishers and boaters in the north-eastern USA were also included because the turtle-fishery interactions were unusual, and, therefore, interesting.

3.3 | Fisheries and fishing gear

Pot fisheries were most often implicated in turtle entanglements (44.4%; n = 91), including snow crab (n = 37), inshore lobster (n = 31), rock crab (n = 10), whelk (n = 8), and hagfish (n = 3) fisheries

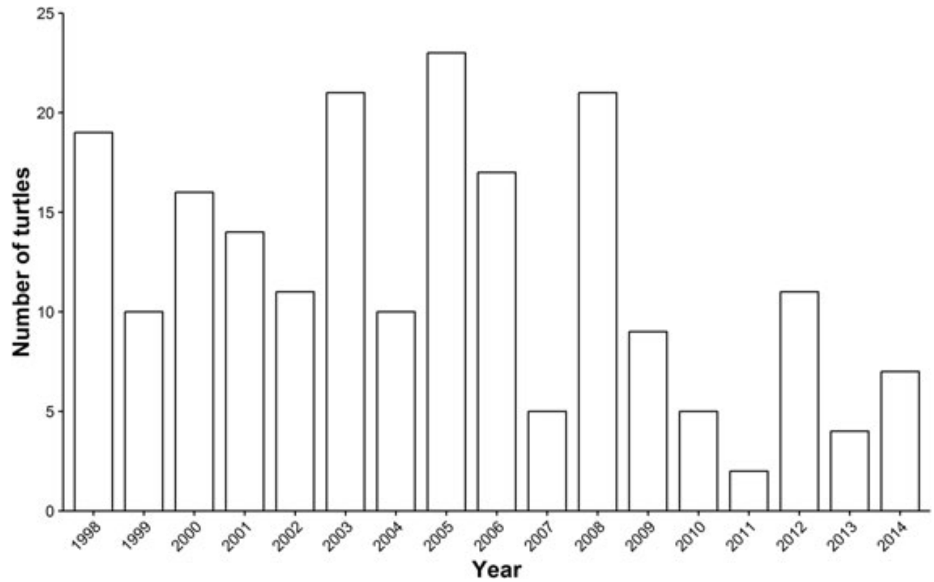

FIGURE 1 Number of entangled leatherback sea turtles reported per year in Atlantic Canada from 1998 to 2014. Reported numbers represent an underestimate of true entanglement incidence owing to reporting biases

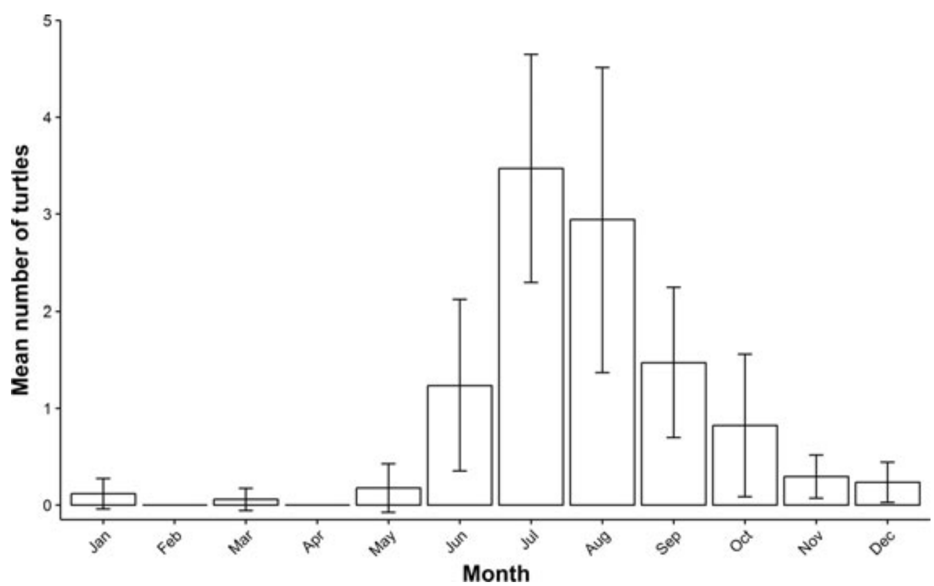

FIGURE 2 Mean number of entangled leatherback sea turtles reported in Atlantic Canada by month between 1998 and 2014 (error bars represent 95% confidence intervals). Reported numbers represent an underestimate of true entanglement incidence owing to reporting biases

(Table 1). Trap net fisheries were involved in the next highest number of entanglements (25.8%; *n* = 53). There were also numerous entanglements involving gill nets (11.7%; *n* = 24), particularly in Newfoundland and Labrador (*n* = 15). Gill nets were mainly targeting groundfish (e.g. Atlantic cod, *Gadus morhua*). Additional entanglements reported from the region corresponded to groundfish longlines, bait nets, and the offshore lobster fishery (where multiple pots are deployed in a string).

The gear component most frequently implicated in turtle entanglements was the main vertical buoy line, commonly associated with pot gear (45.8%; *n* = 94; Table 2). An additional 10.7% of leatherbacks (*n* = 22) were reported entangled in haul-up lines (also known as trip lines, trailer buoy lines or grapple lines), which are accessory buoy lines used to simplify gear retrieval. Other miscellaneous ropes of unknown origin (11.7%; *n* = 24) were the next most common gear type. Mooring lines (mainly associated with trap nets) and fishing nets (e.g. gill nets) were also frequently involved (7.3% each, for moorings and nets; *n* = 15).

Gear loss or damage was noted or described for 23.4% of the incidents (*n* = 48), whereas the other records either did not involve gear loss or at least did not include reference to damage or loss. Gear loss and damage generally resulted from fishermen cutting ropes or otherwise dismantling gear to release an entangled turtle and/or a turtle swimming away with the gear still attached to it (e.g. pots, nets). There were at least eight cases in which turtles were observed dragging multiple pots (e.g. snow crab, lobster pots), or were reported entrapped in multiple pot buoy lines.

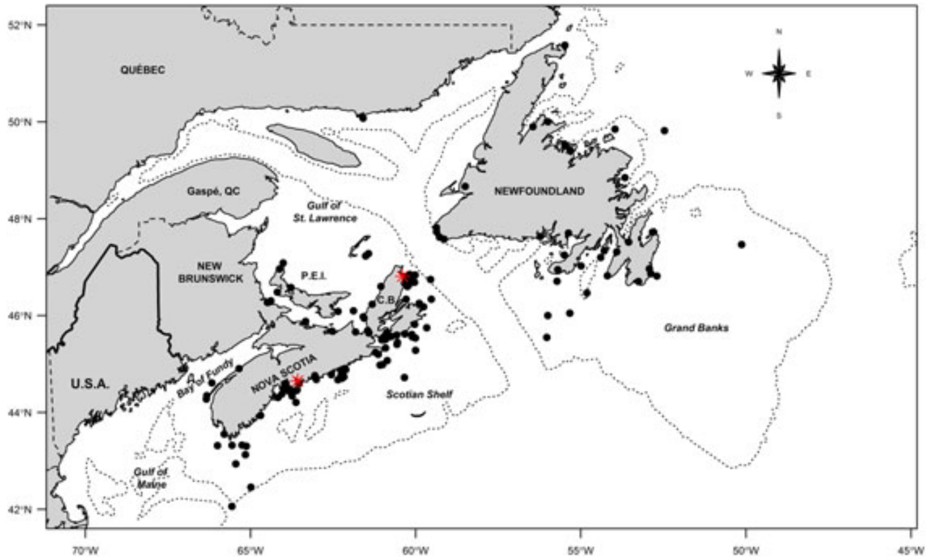

FIGURE 3 Geographic distribution of reported leatherback sea turtle entanglements between 1998 and 2014 in Atlantic Canada. P.E.I. = Prince Edward Island and C.B. = Cape Breton Island, Nova Scotia. Red stars indicate the locations of Canadian Sea Turtle Network field sites in Halifax, Nova Scotia and Neil's Harbour, Cape Breton, Nova Scotia. The solid black line indicates the border between Canada and the United States, dashed lines represent state and provincial boundaries, and dotted lines represent the 200-m isobath. Additional records from Labrador (n = 1) and the north-eastern United States (n = 3) are not pictured

TABLE 1 Fisheries implicated in leatherback sea turtle entanglements in Atlantic Canada from 1998 to 2014

Fishery	Frequency	Percentage of entanglements (%)
Pot*	91	44.4
Trap net	53	25.8
Gill net	24	11.7
Groundfish longline	7	3.4
Rod and reel (tuna/swordfish)	4	2.0
Bait net	3	1.5
Aquaculture	3	1.5
Offshore lobster	2	0.98
Other/Unknown	18	8.8

*Pot fisheries include inshore lobster, snow crab, rock crab, whelk, and hagfish fisheries

TABLE 2 Fishing gear components implicated in leatherback sea turtle entanglements in Atlantic Canada from 1998 to 2014

Part of gear	Frequency	Percentage of entanglements (%)
Main buoy line	94	45.8
Miscellaneous rope	24	11.7
Haul-up buoy line	22	10.7
Mooring line	15	7.3
Net	15	7.3
Trap net (free-swimming)	15	7.3
Head rope	5	2.4
Hook	4	2.0
Bottom longline	3	1.5
Hi-flier line	2	0.98
Other/Unknown	6	2.9

3.4 | Other notable records

While anchored lines were the focus of this study, four reports (including the three records from the north-eastern USA) included leatherbacks externally foul-hooked in rod-and-reel fisheries targeting tuna and swordfish (i.e. hooked on the body rather than hooked on the mouth after pursuing bait).

Three turtles were reported entangled in lines associated with coastal aquaculture operations (e.g. scallop spat collector ropes, lines associated with mussel farm operations).

3.5 | Injuries and mortality

The majority of entangled leatherbacks (84.9%; n = 174) were reported alive and successfully released, and the other 15.1% (n = 31) were reported dead in gear, with drowning or asphyxiation as the most common cause of death. However, because of multiple, strong reporting biases, the number of dead turtles reported here is considered a gross underestimate of actual entanglement-associated mortality, and a true mortality rate cannot be estimated.

Almost all entangled turtles reported alive were entrapped in gear (n = 162; 93.1%), while several live turtles were found free-swimming at sea trailing gear (n = 12; 6.9%). The majority of dead entangled turtles were also found entrapped (n = 22; 71%), while 16.1% were found floating dead at sea with gear still attached (n = 5) and 12.9% were found stranded dead on the coast with gear attached (n = 4).

In order to understand how fixed-gear entanglements may injure and/or kill leatherback turtles, the body parts of the turtle directly affected by the entanglement were identified. Affected body parts could be identified in 58% of cases (n = 119). Of these entanglements, the most common scenario involved line wrapped multiple times around the front flippers (49.6%, n = 59), or encircling both the front

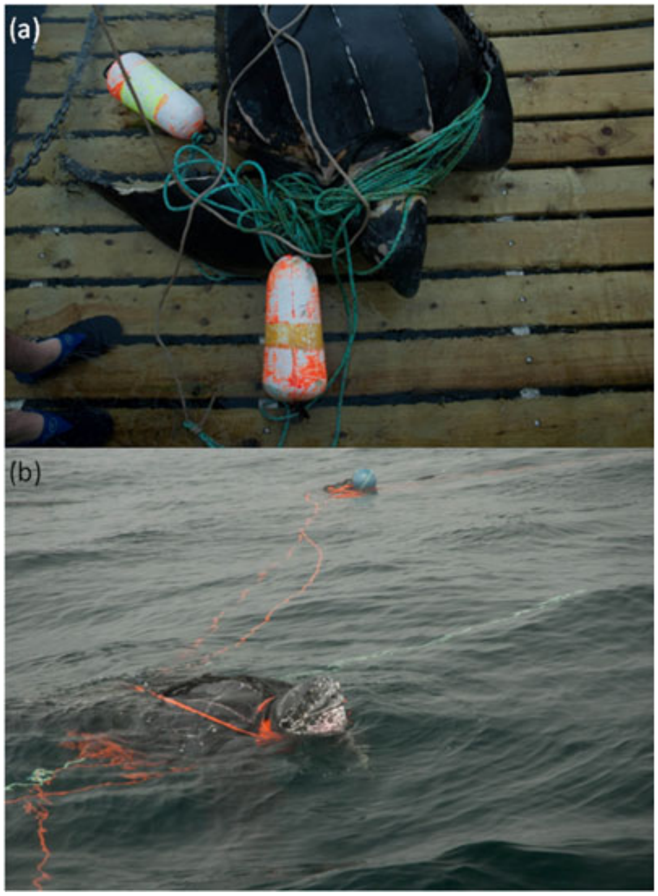

FIGURE 4 Leatherback sea turtles caught in polypropylene lines in Atlantic Canada. Photo credit: Canadian Sea Turtle Network

flippers and the neck (36.1%; *n* = 43; Figure 4), while several (6.7%, *n* = 8) additional turtles were caught only by lines around their head or neck. Several turtles (5.9%; *n* = 7) were corralled in a trap net (e.g. mackerel trap), but were not entangled in gear at the time they were reported. As trap nets include a section of open netting through which target and non-target species enter, a proportion of these turtles may have escaped without further interaction with the gear.

3.6 | Entanglement reporting

Most entanglements were reported by commercial fishers (73.6%; *n* = 151) (Table 3). Other frequent reporters included the general public, such as recreational boat users and tourists (8.8%; *n* = 18), and the CSTN-DFO field research team (8.3%; *n* = 17). Several reports also came from Fisheries and Oceans Canada (DFO) staff (4.4%; *n* = 9). 'Other/Unknown' reporters (2.9%; *n* = 6) included representatives from other non-governmental organizations, commercial mariners, and anonymous reporters.

TABLE 3 Number of entangled turtles reported by various reporter types in Atlantic Canada from 1998 to 2014

Reporter Type	Frequency	Percentage of Entanglements (%)
Fisherman	151	73.6
General public	18	8.8
CSTN field team	17	8.3
Fisheries and Oceans Canada	9	4.4
Fisheries observer	3	1.5
Tour boat operator	1	0.49
Other/Unknown	6	2.9

4 | DISCUSSION

Consistent with other wildlife sightings reporting programmes where socio-economic and psycho-social influences adversely affect reporting (Goff & Lien, 1988; Moore et al., 2010; Senko, Schneller, Solis, Ollervides, & Nichols, 2011), the number of leatherback entanglement reports summarized here should be considered a minimum estimate. Nonetheless, these records identify leatherback interactions with fixed gear as a regular phenomenon and an understudied source of sea turtle mortality in Atlantic Canada.

4.1 | Temporal patterns and entanglement reporting

As has been noted previously, patterns of reported leatherback sightings (and also entanglements in this case) do not precisely mirror patterns of turtle abundance, but instead reflect periods of highest activity in time-managed (seasonal) fixed-gear fisheries operating at various times during the broader leatherback turtle foraging period in Canadian waters (James et al., 2006). Most reported entanglement incidents took place in July and August, which is when numerous fisheries are active in Atlantic Canada and many turtles have moved from offshore waters onto the continental shelf and are actively foraging (James, Myers, & Ottensmeyer, 2005). There were a number of reports in cooler months; however, the general decline in reporting in late summer is an artifact of decreased observer effort (when relatively fewer fishers and recreational boaters are active on the seascape) and precedes the actual departure of most turtles from Canadian waters (James et al., 2006). Most dead, stranded turtles found in the winter months were assumed to have died the preceding autumn because of the extensive degree of decomposition observed.

Inter-annual variation in the number of reported leatherback entanglements is a function of the number of turtles present in the region; fishing effort and the types of fisheries (and associated gears) that overlap in space and time with turtle distributions; the number of turtles that get entangled; and the motivations and/or sensitivities of those who observe or hear about entanglement events. Inter-annual variability in entanglement reporting in some cases reflects the early arrival of turtles in shelf waters, associated with an early spring. For example, in 2006 and 2012 the arrival of relatively large numbers of leatherbacks in near-shore areas on the eastern Scotian Shelf (Figure 3) approximately a month earlier than expected led to interactions with the inshore lobster fisheries. These fisheries are normally closed when most leatherbacks arrive in the area during a more 'typical' year. The converse can also be true, as was the case in 2014 when a late departure of turtles from the Gulf of St. Lawrence contributed to multiple entanglement incidents in the Northumberland Strait between New Brunswick and Prince Edward

Island, where the lobster season runs until October (DFO lobster fishing area [LFA] 25).

In recent years, the absolute number of reported entanglements has decreased, possibly because of a decreased incidence in entanglement, but more likely owing to diminished reporting effort by the fishing industry. The majority of leatherback turtle entanglements were contributed by commercial fishermen, most of whom responded to the grassroots sea turtle public education campaigns in rural fishing communities of Atlantic Canada (which promote reporting of sea turtle sightings) when these campaigns were still relatively new. This highlights the importance of not only maintaining, but also diversifying community outreach and educational initiatives through time, and in some cases incentivizing reporting of fishery interactions in non-monetary ways to heighten both awareness of sea turtles and understanding of threats (Martin & James, 2005b).

Other social factors also have an important role in influencing reporting effort, as the motivation of a fisher to report sightings (particularly entanglements and entanglement-related mortality) may be affected by a perceived threat of punitive action by management authorities, or other livelihood impacts (Martin & James, 2005b). In particular, a reduced proclivity for resource users to share information about interactions with endangered species (including leatherbacks) may be related to the implementation of Canada's federal Species at Risk Act (SARA), which came into full effect in June 2004 and includes prohibitions against harming, harassing, or killing listed endangered species, including the leatherback. A reduction of information sharing surrounding listed species by various stakeholder groups, and especially those participating in activities identified as threats, may be an unintended outcome of legislation such as SARA (Martin & James, 2005a).

4.2 | Geographic patterns

In general, spatio-temporal trends in reported entanglement events reflect the overlap between the typical seasonal movement patterns of leatherback turtles in Atlantic Canada (as established from fishery-independent satellite telemetry data; James, Ottensmeyer, & Myers, 2005) and seasonal patterns in fishing effort. Since neither fishing effort nor turtles are randomly distributed in the oceanographic environment, highly productive areas that are also popular fishing grounds contribute a disproportionate number of sightings (James et al., 2006; Lewison & Crowder, 2007). For example, the concentration of entanglements in the vicinity of the Canso Causeway, which connects Cape Breton Island to mainland Nova Scotia, may result from both the combination of fishing effort and turtles seeking migratory routes but encountering a barrier (in this case the causeway itself), resulting in periods of increased turtle density in that area.

There is a bias in the spatial pattern of reported entanglements stemming from the CSTN-DFO active at-sea field research programmes off Halifax, Nova Scotia, and northern Cape Breton Island, Nova Scotia. In both areas, vessel surveys for turtles are conducted annually and within the same timeframe across years (Archibald & James, 2016), increasing the probability of an entangled turtle being encountered and documented in these locations. In addition to dedicated turtle surveys, public awareness of the CSTN sea turtle sightings programme and the group's interest in, and capacity for, responding to stranded and/or entangled turtles is relatively higher in coastal communities proximate to field research areas. This may increase reporting by the public, further contributing to biases in the spatial distribution of entanglements reported in those areas.

There were relatively few records from the Gulf of St. Lawrence in the vicinity of northern New Brunswick; the Gaspé Peninsula, Québec; and the north shore of Québec. This may reflect a language barrier in reporting effort from francophone jurisdictions. Tracking and sighting data indicate leatherbacks are occasionally observed in these areas; thus entanglement represents a likely hazard there, too.

4.3 | Fisheries and fishing gear

Identifying fisheries implicated in entanglements is essential to designing appropriate mitigation measures. In this study, whenever possible, the specific component of the fishing gear that was directly implicated in each entanglement was identified, revealing the most typical entanglement scenarios for leatherbacks in Canadian waters. This type of specific information is critical not only for understanding the nature of entanglement itself, but also for discussing entanglement scenarios and potential mitigation strategies with members of the fishing community. The fishing gear components implicated in leatherback fixed-gear entanglements in Atlantic Canadian shelf waters comprise vertical lines (e.g. main buoy lines) and horizontal lines (normally floating at the surface; e.g. haul-up ropes, head ropes). Insight into the three-dimensional use of the water column by leatherbacks demonstrates that their dives at northern temperate latitudes are largely limited to the surface mixed layer, where interaction with buoy lines is most likely (Hamelin, Kelley, Taggart, & James, 2014). While there is great variety in types of gear fished, fishing practices, and how leatherbacks interact with gear across their range, the gear components identified here can inform leatherback bycatch management in many fisheries across jurisdictions.

4.3.1 | Pot fisheries

Pot fisheries were associated with the highest number of entanglement reports in this study, particularly those targeting snow crab (*Chionoecetes opilio*) and inshore American lobster (*Homarus americanus*). These and other pot fisheries normally use weighted traps attached to single buoy lines. Vertical buoy lines running to traps on the ocean floor are also often equipped with a secondary haul-up line. Only a few previous studies (Adimey et al., 2014; Allen, 2000; James, Ottensmeyer et al., 2005; Zollett, 2009) have investigated the role of pot gear in leatherback entanglements, despite its prevalence throughout key temperate coastal foraging habitat used by this species; the vulnerability of leatherbacks due to their foraging activity in the upper water column; and the entanglement risk this gear also poses to other endangered species (e.g. North Atlantic right whale; Myers, Boudreau, & Kenney, 2006).

The snow crab fishery was implicated in the most pot fishery entanglement incidents during the study period. Changes in fishing effort may reduce entanglement rates. For example, there has been a recent shift from a summer to a spring snow crab fishery by a portion of the fleet on the eastern Scotian Shelf (Figure 3), reducing the overlap between this fishery and leatherback turtle distributions.

The present study suggests that leatherback entanglements in the inshore lobster fishery have been grossly underestimated in the past. A preliminary evaluation of the potential impacts of fixed gear on leatherback turtles by DFO relied largely on fishery observer data and voluntary recording of interactions in fisher log books, yielding only two (log book) records of lobster fishery interactions with leatherbacks (DFO, 2012b), in contrast to the dozens of records directly reported and compiled here. Despite the magnitude of the inshore lobster fishery (representing the largest industry in rural coastal areas in terms of related employment and overall regional seafood landing values (Statistics, DFO-Ottawa, Ontario K1A 0E6)), it receives limited fishery observer coverage (DFO, 2012b). The threat the inshore lobster fishery presents is perhaps greatest in adjacent New England, USA, where the fishery is open year-round (versus time-managed in Canada), with pot limits between 800 and 1945 per licence holder depending on the fishing area (Code of Federal Regulations, 2015), versus 250-400 pots for most Canadian licences (DFO, 2011a).

Lobster fishing in Atlantic Canada is time- and area-managed, with most fishing effort concluding by the end of June in many of the areas where leatherbacks are also known to seasonally aggregate. The result is that leatherback–fishery interactions may be relatively infrequent in most years, as turtle density on the continental shelf increases markedly in July and August. However, some LFAs on the Scotian Shelf and LFA 25 in the Northumberland Strait are open to fishing during the period when the local seasonal density of leatherbacks is high, and where entanglements have been reported.

Pot fisheries are most commonly implicated in entanglements of marine turtles and whales (Allen, 2000; Benjamins, Ledwell, Huntington, & Davidson, 2012; Dayton & Thrush, 1995; Johnson et al., 2005; Knowlton & Kraus, 2001; Kraus et al., 2005; Zollett, 2009) because of the serious threat posed by buoy lines. The data presented here confirm that other fisheries in Atlantic Canada that are characterized by significantly less fishing effort still pose entanglement hazards for foraging turtles as they, too, employ vertical buoy lines (e.g. rock crab, whelk, and hagfish pots). Furthermore, we hypothesize that many of the 'miscellaneous' ropes referenced in entanglement reports, which could not be specifically identified, originate from buoy lines associated with these and other fisheries.

4.3.2 | Trap net fisheries

Trap net fisheries were also responsible for many turtle entanglements during the study period. However, importantly, a strong bias in the number of reports associated with this fishery stems from the fact that CSTN-DFO field research and vessel surveys overlap in time and space with trap net fishery effort off south-west Nova Scotia. Goff and Lien (1988) and McAlpine, James, Lien, and Orchard (2007) also identified multiple leatherback interactions with trap nets (targeting cod) off Newfoundland. Trap nets are known to interact with sea turtles in coastal areas globally (Cheng & Chen, 1997; Epperly, Braun, & Veishlow, 1995; Gilman et al., 2010; Lutcavage & Musick, 1985).

Trap nets are fixed, passive net structures, normally set in coastal areas. They may have several different configurations depending on target species, where they are fished, tidal magnitude, and water depth. Passive trap nets may be set in shallow water and held in place with a series of poles driven into the ocean floor (e.g. pound nets and weirs; FAO Fisheries and Aquaculture Department, 2010). An alternative configuration, which is associated with most of the entanglements reported here, is a bowl-shaped net suspended in the water column with the open top of the net suspended from the sea's surface by an encircling "head rope" supported by a continuous series of small floats. The sides, bottom, and overall shape of the net are maintained by an extensive series of taut anchor (mooring) lines, each normally associated with an attached haul-up line. In all cases, trap nets integrate a leader, which is a wall of netting that typically runs perpendicular to the shoreline and passively directs schools of fish (target species) – but also bycatch species, such as turtles – into the body of the trap.

Turtles become corralled (free-swimming) in the body of the trap net, or become entangled in the buoy lines, haul-up lines, mooring lines, or head rope associated with the trap (Figure 4b). While trap nets have been fished throughout the summer months, including during periods of peak turtle abundance, both the number of trap nets and their typical fishing season have been more variable in recent years.

4.3.3 | Other fishery interactions

A number of leatherbacks were also caught in either gill nets or bait nets targeting groundfish or herring/mackerel, respectively. The majority of these records came from Newfoundland and Labrador, with additional incidents throughout Nova Scotia and Prince Edward Island (Figure 3). It is possible that regional variation in fishing practices may make gill nets a more localized hazard for leatherbacks in specific areas (e.g. Newfoundland). However, reports of leatherbacks captured in gillnets often specified that the entanglement occurred not in the netting itself, but in a buoy line associated with the net infrastructure. This is consistent with the present results identifying buoy lines as a primary threat. The current study includes relatively few turtles reported entangled in groundfish longline gear (buoy lines or corresponding surface hi-flier lines), despite relatively high fishing effort and spatio-temporal overlap with leatherback turtle distributions.

Rod-and-reel fisheries targeting large pelagic fish (swordfish and tuna) represented a rare type of reported gear interaction, and leatherbacks were reported as foul-hooked in these instances. Three of the four records were reported by fishers off of the eastern coast of the USA. Hook-and-line interactions with marine animals have been documented elsewhere (e.g. Florida; Adimey et al., 2014), but these incidents are exceedingly rare for leatherbacks compared with other sea turtles or marine mammals.

Although entanglement in aquaculture gear has been identified as a potential threat to marine mammals (Johnson et al., 2005), to date, there are few reported incidents involving sea turtles. However, there were three entanglements in lines associated with both mussel and scallop farming documented in the present study. This probably underestimates the true number of interactions, as aquaculture operators were not targeted by outreach campaigns soliciting turtle sightings. Aquaculture is an understudied source of impact that should be taken into account in future entanglement research and mitigation efforts.

4.3.4 | Unmonitored fishing gear

It should be noted that unmonitored fishing gear can be considered a form of 'ghost' fishing gear because it is effectively abandoned for extended periods. This gear can be equally, and potentially more, hazardous to turtles than tended fishing gear because turtles experiencing prolonged entanglements in unmonitored gear have poor prospects for survival. This issue is relevant to the current study because many of the reported trap net entanglements took place when the gear was no longer being actively fished, but associated gear components, including structural anchor lines, remained in the water for varying periods of time before being hauled. When traps were left to soak untended for several days or when traps were not completely dismantled, the infrastructure components incorporating vertical and surface lines continued to present an entanglement hazard to leatherbacks (Figure 4a). This type of ghost fishing is not usually considered when evaluating bycatch or entanglements of marine animals (Laist, 1995). However, because of its relevance to incidental capture of non-target species such as turtles, we suggest that it should be considered in fishery management planning.

4.3.5 | Relative threat of temperate North Atlantic pelagic longline fisheries

Several studies have highlighted the threat pelagic longline fisheries pose to sea turtles globally (Lewison, Freeman, & Crowder, 2004; Lewison & Crowder, 2007; Wallace et al., 2010, Wallace et al., 2013). Importantly, sea turtle (both leatherback and cheloniid turtle) interaction rates with this type of fishing gear are high, and associated internal hooking and/or forced submergence regularly result in mortality of cheloniid turtles (Àlvarez de Quevedo, San Félix, & Cardona, 2013; Casale, Cattarino, Freggi, Rocco, & Argano, 2007; Swimmer et al., 2006). However, a review of published literature reveals that there has been a disproportionate level of emphasis and scrutiny placed on pelagic longline fisheries with respect to impacts on leatherback turtles in temperate north-west Atlantic waters (e.g. Fossette et al., 2014), while leatherback interactions with fixed gear have been largely unexplored in this region. Much of this misdirected emphasis on pelagic longline fisheries as the key threat to leatherbacks in this area may stem from a bias among researchers to focus on bycatch in those fisheries where observer data are most readily accessed and plentiful and to assume common risk factors for all sea turtles by grouping leatherbacks with cheloniid turtles (which often co-occur in bycatch but interact with the gear in different ways). Generalizing sea turtle bycatch in this way fails to recognize how the fundamentally divergent biology, morphology, and seasonal distributions of leatherbacks influence both their susceptibility to incidental capture in different fisheries and associated mortality rates.

Cheloniid turtles interacting with pelagic longlines are normally hooked in the mouth or swallow the hook (Garrison & Stokes, 2014; Lewison, Freeman et al., 2004; Sales et al., 2010; Watson, Epperly, Shah, & Foster, 2005), while leatherbacks are typically foul-hooked externally and entangled in the monofilament lines because their dietary preferences (i.e. jellyfish; Heaslip et al., 2012; Wallace et al., 2015) generally do not lead them to target baited hooks (Witzell & Cramer, 1995; Watson et al., 2005). Moreover, because of their sheer size and strength, leatherbacks may be less susceptible to drowning in North Atlantic pelagic longline gear as they can normally return to the surface to breathe even when hooked/entangled (Witzell & Cramer, 1995). Therefore, mortality rates of North Atlantic pelagic longline-caught leatherbacks, both at the time of release and post-release, are probably much lower than those of cheloniid turtles. It is important to note that this outcome may be specific to the temperate north-west Atlantic. The impact of the pelagic longline fishery on leatherback turtles in other areas of the world may be more lethal because of differences in fishing practices (e.g. depth at which gear is set; soak time) and environmental conditions (e.g. turtles may be less likely to survive when caught in warmer waters).

In contrast, because fixed gear is heavily weighted and/or anchored, it may pose an immediate threat to leatherback survival when they are captured at depth. Turtles caught in fixed gear can also be forcibly submerged by a rising tide or through their own escape behaviour. In light of these observations, a higher mortality rate could be expected for leatherbacks entangled in fixed-gear fisheries relative to those in pelagic longlines in their North Atlantic high-latitude foraging areas. While some mitigation measures have been outlined for sea turtles interacting with pelagic longlines in Canadian waters (DFO, 2011b), efforts to mitigate sea turtle entanglement in fixed gear have not yet been pursued.

4.4 | Mechanisms of entanglement, injuries, and mortality

The fishery interactions reviewed in this study, with most turtles held fast by lines wrapped tightly and multiple times around the flippers, suggest that turtles are typically unable to free themselves from entanglements in fixed gear. Instead, their survival prospects depend on human (normally fisher) intervention to safely release them from gear. Few studies report on the mechanics of turtle-fishery interactions. Here, it was determined that the front flippers and the neck are the primary body parts entangled in fishing lines and that both vertical and horizontal lines pose a threat. Identifying which body parts are implicated in entanglements is relevant to understanding how the behaviour of leatherbacks makes them vulnerable to incidental capture, and how fishing practices might be modified to mitigate entanglement and/or enhance post-release leatherback survival.

Field observations during the present study of both free-swimming leatherbacks (including turtles propelling themselves into gear) and turtles entrapped in gear suggest that while foraging in shelf waters, many, if not most, entangled leatherbacks may initially intercept a vertical line in the recess between the neck and the humerus of a front flipper (Figure 5). The turtle then continues to swim forward (reverse propulsion is not exhibited by this species), with the line slipping along in the recess until it reaches the surface buoy, which lodges in the recess, at least momentarily. At this point, if not before, the turtle attempts to push the buoy and line away from the body with one or both front flippers, or attempts to swim away with broad, raised flipper strokes (akin to those observed during peak swim speeds), securing a half-hitch around the humerus. The turtle then begins to struggle, swimming in all directions, flailing the flippers, diving, and rolling – behaviour that has been observed among leatherbacks agitated by the presence of predators (Engbring, Idechong, Cook, Wiles, & Bauer,

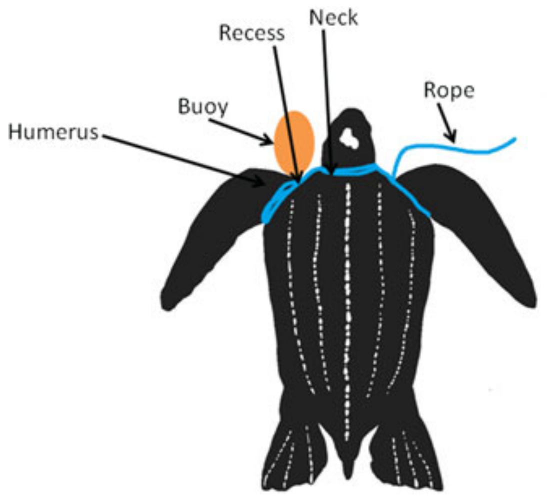

FIGURE 5 Typical gear configuration on an entangled leatherback sea turtle in Atlantic Canada.

1992) or unwelcomed mating attempts (Reina, Abernathy, Marshall, & Spotila, 2005) – with entangling rope(s) repeatedly encircling the flippers and neck. When there is an abundance of slack line involved, the severity of the entanglement, in terms of the amount of line interacting with the turtle, is typically increased (Figure 4). These scenarios can lead to drowning when turtles are forcibly submerged after successive turns of rope on the body have shortened the weighted vertical line to which they are attached, particularly when the tide rises. Surface entanglements may also result in suffocation when lines encircle the neck and constrict the airway. Therefore, slack lines associated with fixed gear increase the hazard of the gear both in terms of the likelihood and severity of interactions.

Some of the turtles that do not die shortly after becoming entangled, but are released alive, will eventually succumb to their injuries. Entanglement-related injuries can result in reduced feeding efficiency, impaired locomotion, exertional myopathy, and deadly infections (Cassoff et al., 2011; Innis et al., 2010; Phillips, Cannizzo, Godfrey, Stacy, & Harms, 2015; Snoddy & Williard, 2010). Some turtles, as documented here, are also released with gear still attached, which can result in prolonged, debilitating health complications or death. Tight wraps of rope around the flippers, characteristic of most entanglements, can also severely restrict or stop blood flow, before release or afterwards (if gear is not completely removed), resulting in reperfusion injuries or necrosis and loss of the limb, an injury that results in mortality (Innis et al., 2010). Unlike other sea turtle species, leatherback turtles do not survive long-term in captivity and the rehabilitation of debilitated leatherbacks is usually not feasible (Jones, Salmon, Wyneken, & Johnson, 2000; Levy, King, & Aizenberg, 2005). In addition to documenting long-term outcomes of turtles released from entanglement (using biotelemetry, mark–recapture methods, etc.), future entanglement research must assess the short- and long-term effects of capture stress. For example, field protocols should be implemented among entanglement first-responders (fishers and conservation groups with this mandate) to safely and effectively release turtles from gear, while also assessing and documenting injuries and indices of animal health. This could provide insight into the long-term effects of entanglement.

4.5 | Policy implications and mitigation

The present efforts to understand leatherback–fishery interactions in Atlantic Canada using citizen reporting networks highlight fixed-gear fisheries at high latitudes as a potentially significant and historically under-appreciated source of mortality for this endangered species. This threat should be evaluated in other jurisdictions that host foraging populations of leatherbacks. As the present results demonstrate, the most effective mitigation strategies that meet both species conservation objectives and socio-economic priorities of resource users may not necessarily involve time–area changes to the management of fisheries, but instead could address the specific mechanisms of identified threats (in this case, the line components of fishing gear). Entanglement mitigation should address both entanglement prevention and maximizing survivorship of turtles (while they are entangled and after release). Thus, effective mitigation options may include changes to fishing gear or practices, as well as promotion of safe disentanglement procedures to enhance animal welfare. The present study demonstrates that the involvement of fishers will be important in the development and implementation of corresponding bycatch mitigation solutions.

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