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Abstract—Fisheries bycatch is posited to be a leading cause of decline in abundance of Atlantic leatherback turtles (*Dermochelys coriacea*). However, although this species regularly interacts with fisheries across its range, movements and postrelease survival of leatherbacks remain largely unstudied. Such research is lacking because sampling opportunities are unpredictable and logistically challenging. Here, movements of 4 leatherbacks equipped with satellite tags following incidental capture in fixed-gear fisheries in Nova Scotia, Canada, are presented, alongside results from previous postentanglement tracking of 15 leatherbacks tagged throughout the Atlantic Ocean. Mean tracking duration after tagging was 232.58 d (standard deviation 165.61; sample size=19), comparable with what has been reported for fishery-independent deployments of satellite tags on leatherbacks. This result indicates that, provided they are released carefully and completely from fishing gear, many leatherbacks survive entanglement events without apparent long-term effects.

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Postrelease movements of leatherback turtles (*Dermochelys coriacea*) following incidental capture in fishing gear in the Atlantic Ocean

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It is challenging to quantify the effects of anthropogenic threats to marine species, especially for highly migratory animals, such as marine mammals, sharks, and sea turtles (Lascelles et al., 2014). However, the use of electronic tagging technologies, including satellite telemetry, can provide insight into bycatch risk (Witt et al., 2011; Kindt-Larsen et al., 2016) and has provided indirect (Henderson et al., 2020) and direct evidence for mortality associated with fishery interactions (Byrne et al., 2017; Benson et al., 2018). Application of satellite transmitters to incidentally caught sea turtles has also facilitated evaluation of postrelease mortality after fishery interactions (Chaloupka et al., 2004; Swimmer et al., 2006; Snoddy and Williard, 2010).

In the Atlantic Ocean, leatherback turtles (*Dermochelys coriacea*) interact with numerous fisheries and gear types (Wallace et al., 2010). The capture of reproductive leatherbacks in artisanal gill nets is especially concerning for the Northwest Atlantic leatherback turtle subpopulation because of the high potential for mortality (Wallace et al., 2013; NMFS and USFWS, 2020). In Trinidad, where one of the largest nesting assemblages of leatherbacks is found, coastal gill-net fisheries are estimated to kill 1000 leatherbacks annually (Lee Lum, 2006). Although additional studies are needed to quantify the extent of this risk and mortality rates in coastal waters near nesting beaches, bycatch in coastal gill-net fisheries has also been identified as a threat in French Guiana (TEWG, 2007), Colombia (Patiño-Martinez et al., 2008), and Brazil (Lewison and Crowder, 2007).

Atlantic Canada, a region that includes the provinces of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador, is a primary foraging area for leatherbacks in the Northwest Atlantic Ocean, where incidental capture in fixed-gear fisheries has been identified as a primary threat to this species (Hamelin et al., 2017). However, capture rates, rates of mortality during capture, and postrelease mortality of leatherbacks in this area are not well understood. Here, satellite tracking data are presented for leatherbacks released following incidental entanglement in fixed-gear fisheries in Atlantic Canada. Given the rarity of opportunities to satellite tag leatherbacks entangled in fixed fishing gear, additional published satellite tracks of leatherbacks released following incidental entanglement (sample size [n]=15) were also reviewed. These tracks include records from the Northwest Atlantic Ocean, Southwest Atlantic Ocean, and Northeast Atlantic Ocean.

Materials and methods

Four leatherbacks were tagged in coastal waters off Nova Scotia, Canada (turtles A–D in Table 1). These 4 turtles were found entangled in lines associated with fish traps

Table 1

Details of fishery interactions and satellite tracking for leatherback turtles (*Dermochelys coriacea*) satellite tagged and released following incidental capture in fishing gear in 2003–2012 in the Northwest Atlantic Ocean (NWA), Southwest Atlantic Ocean (SWA), and Northeast Atlantic Ocean (NEA). Mean travel rates are given with standard deviation in parentheses. A dash indicates a field that was not reported in the reviewed study. CCL=curved carapace length.

Turtle	Date deployed	Gear type	Location	Sex	CCL (cm)	Tag attachment type	Days tracked	Mean travel rate (km/h)	Source
A	16-Jul-2003	Fish trap (line entanglement)	Nova Scotia, Canada (NWA)	U	134.0	Harness	537	1.13 (0.79)	This study
B	12-Aug-2003	Fish trap (line entanglement)	Nova Scotia, Canada (NWA)	U	140.0	Harness	210	1.19 (0.54)	This study
C	18-Jul-2008	Fish trap (line entanglement)	Nova Scotia, Canada (NWA)	M	148.2	Direct	311	1.38 (0.76)	This study
D	4-Jul-2012	Fish trap (line entanglement)	Nova Scotia, Canada (NWA)	F	144.0	Direct	212	1.43 (0.96)	This study
E	12-Feb-2006	Driftnet	São Paulo, Brazil (SWA)	F	153.0	Harness	97		Almeida et al. (2011)
F	15-Jun-2005	Pelagic longline (mainline or branch lines)	High seas (SWA)	F	148.0	Harness	313		López-Mendilaharsu et al. (2009)
G	31-Jul-2006	Pelagic longline (mainline or branch lines)	High seas (SWA)	M	159.0	Harness	237		López-Mendilaharsu et al. (2009)
H	14-Aug-2006	Pelagic longline (mainline or branch lines)	High seas (SWA)	U	126.0	Harness	349		López-Mendilaharsu et al. (2009)
I	29-Oct-2006	Artisanal bottom-set gill net	Rio de la Plata Estuary, Uruguay (SWA)	F	155.5	Harness	631		López-Mendilaharsu et al. (2009)
J	1-Sep-2005	Lobster pot (line entanglement)	0.2 km from Cuas Harbour, Ireland (NEA)	F	–	Harness	375		Doyle et al. (2008)
K	29-Jun-2006	Salmon drift net	0.5 km from Cuas Harbour, Ireland (NEA)	M	–	Direct	233		Doyle et al. (2008)
L	19-Aug-2007	Fixed gear (line entanglement)	Nantucket Sound, USA (NWA)	M	140.7	Direct	34		Dodge et al. (2014); Dodge[1]
M	29-Aug-2007	Fixed gear (line entanglement)	Cape Cod Bay, USA (NWA)	M	143.2	Direct	18		Dodge et al. (2014); Dodge[1]
N	29-Aug-2007	Fixed gear (line entanglement)	Nantucket Sound, USA (NWA)	U	123.0	Direct	16		Dodge et al. (2014); Dodge[1]
O	22-Sep-2007	Fixed gear (line entanglement)	Cape Cod Bay, USA (NWA)	U	137.5	Direct	183		Dodge et al. (2014); Dodge[1]
P	1-Oct-2007	Fixed gear (line entanglement)	Cape Cod Bay, USA (NWA)	F	136.0	Direct	35		Dodge et al. (2014); Dodge[1]
Q	23-Aug-2008	Fixed gear (line entanglement)	Nantucket Sound, USA (NWA)	M	146.4	Direct	234		Dodge et al. (2014); Dodge[1]
R	28-Aug-2008	Fixed gear (line entanglement)	Nantucket Sound, USA (NWA)	U	140.0	Direct	191		Dodge et al. (2014); Dodge[1]
S	3-Sep-2009	Fixed gear (line entanglement)	Nantucket Sound, USA (NWA)	M	155.0	Direct	203		Dodge et al. (2014); Dodge[1]

[1] Dodge, K. 2021. Personal commun. Fish. Sci. Emerg. Tech., New England Aquar., 1 Central Wharf, Boston, MA 02110.

(Table 1), and they presented with rope wrapped multiple times around the front flippers, or the flippers and neck, as is commonly documented among leatherbacks entangled in fixed-gear fisheries in Atlantic Canada (Hamelin et al., 2017). Following complete removal of all entangling fishing gear, each turtle was visually examined for injuries, and its condition was assessed. Turtles were measured and photographed. Sex was determined for individuals with curved carapace length (CCL) ≥145 cm on the basis of phallus display or tail morphology, and turtles with CCL <145 cm were classified as juveniles (Eckert, 2002). Tissue samples were obtained by using a 5-mm biopsy punch (Acuderm Inc.[1], Fort Lauderdale, FL), and identification tags (Monel flipper tags and passive integrated transponders) were applied.

Turtles were equipped with satellite transmitters (models SSC3 [n=1], SPOT3 [n=1], or MK10-AF [n=2], Wildlife Computers Inc., Redmond, WA), by using harnesses (n=2) or direct attachment (n=2) (Hamelin and James, 2018). After tagging, turtles were immediately released. Location data were transmitted through the Argos satellite network, and locations classified as LC3, LC2, LC1, and LC0 and estimated to be within 150 m, 150–350 m, 350–1000 m, and >1000 m of true locations were retained for analysis (Fig. 1). Data processing and analyses were conducted by using statistical software R, vers. 3.6.1 (R Core Team, 2019), and tracking data were plotted by using ArcMap 10.7 (Esri, Redlands, CA). Protocols for disentanglement, sampling, and satellite-tag attachment were approved by the Dalhousie University Committee on Laboratory Animals or the Fisheries and Oceans Canada Maritimes Animal Care Committee to meet standards established by the Canadian Council on Animal Care. Data and interaction details for turtles E–S (Table 1) were obtained from previously published tracks of satellite-tagged leatherbacks following their release from fishing gear.

Results and discussion

Turtles A–D were active and responsive at the time of release; they displayed only minor abrasions and vigorous movements. Satellite tracking durations spanned 210–537 d, with an average of 9754 km (standard deviation [SD] 3790.6) travelled and mean travel rates from 1.130 km/h (SD 0.791) to 1.430 km/h (SD 0.960) (Table 1). Turtle B immediately swam south and departed continental shelf waters after release. However, the other turtles remained in northern continental shelf waters off Canada and the United States throughout the summer–fall foraging season, before eventually migrating to low latitudes for the winter (Fig. 1). Such behavior is consistent with movement patterns exhibited by free-swimming leatherbacks tracked following directed-capture sampling in Canada or from nesting beaches (James et al., 2005). Tags on 3 turtles ceased transmitting data during the winter following tag deployment; however, turtle A was tracked through a second foraging season in waters off Atlantic Canada (for a total tracking duration of 537 d).

Travel rates for turtles A–D were similar to those of leatherbacks tracked following directed capture off Nova Scotia (Jonsen et al., 2006) and after departing nesting beaches in Trinidad (Eckert, 2006) and French Guiana (Fossette et al., 2008). Three of the 4 turtles were not observed again after tagging. However, Turtle D was subsequently recorded nesting at Matura Beach, Trinidad, in 2014, 2017, and 2019 (when replacement satellite tags were deployed) and was tracked back to waters off Atlantic Canada in 2017, 2019, and 2020. Turtle D's foraging, migratory, and nesting history spanning 8 years from the first tag deployment is compelling evidence for a lack of long-term behavioral or fitness effects associated with the original capture and tagging of this individual.

The mean tracking duration for leatherbacks after they were disentangled and released (all deployments, Table 1) was 232.58 d (SD 165.61; n=19). Most (74%) leatherbacks were tracked for over 100 d, with many completing large-scale migrations throughout the deployment period (Doyle et al., 2008; Almeida et al., 2011; Dodge et al., 2014) (Fig. 1). The mean tracking duration of leatherbacks after disentanglement and release in our analysis was not significantly different from the tracking durations of live-captured leatherbacks documented by Hamelin and James (2018) (P=0.538). Importantly, the sample considered here includes leatherbacks interacting with a variety of fisheries throughout the Atlantic Ocean and encompasses turtles that presented as vigorous and lacking apparent external injuries at the time of tagging (turtles A–D) (Doyle et al., 2008) and others that had clearly sustained injuries (Innis et al., 2010; Dodge et al., 2014). The tracking results here (turtles A–S, Table 1), coupled with the high rate of scarring likely caused by fishery interactions observed among nesting and foraging leatherbacks (Archibald and James, 2018), indicate that many leatherbacks can recover from entanglement events. Dodge et al. (2014) established that some of the turtles they tracked were previously entangled, and at least one tagged turtle had sustained injuries from constricting and cutting lines (Innis et al., 2010). Others, however, only had minor abrasions. It is unclear if the short tracking durations (<50 d, Table 1) among the leatherbacks considered from other studies correspond to turtles that had severe entanglement injuries and were judged by Innis et al. (2010) to be in relatively poor health.

The satellite tracking data reviewed and presented here are from a variety of satellite transmitter models with varying sensor options, sampling and transmission regimes, and battery capacities. Biofouling, broken antennas, and premature detachment can contribute to cessation of satellite tag transmissions, affecting tracking durations (Hays et al., 2007). These confounding factors,

[1] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

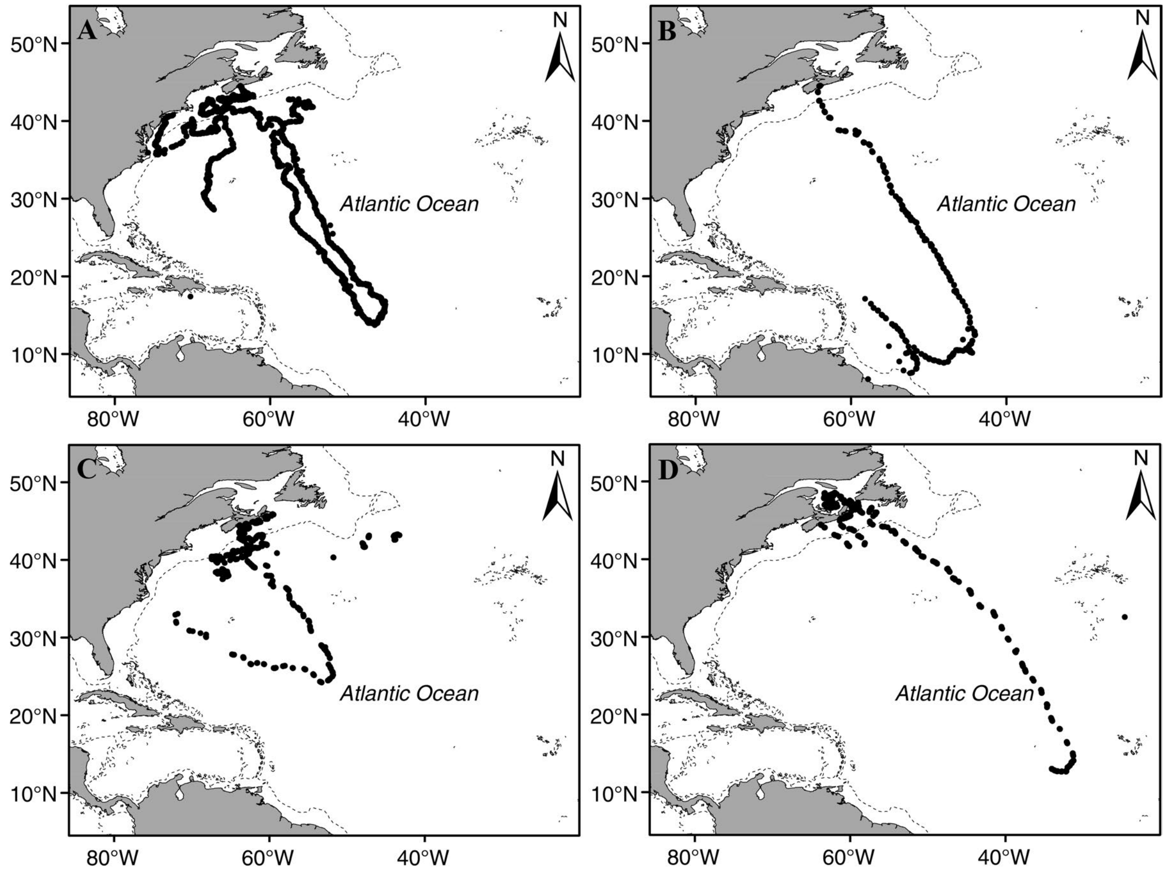

Figure 1

(**A–D**) Maps showing the tracks of 4 leatherback turtles (*Dermochelys coriacea*) equipped with satellite tags following incidental entanglement in fishing gear off Nova Scotia, Canada, during 2003–2012. The dashed line indicates the 1000-m isobath.

which are normally impossible to diagnose remotely, make it difficult to identify events of true turtle mortality, especially when environmental data, such as depth, temperature, or light level, are not available.

Uncertainty regarding how representative the sample we considered is of post-entanglement outcomes for leatherbacks results from the relatively low number of entangled turtles equipped with satellite tags and the lack of standardized biomedical assessment criteria for classifying entanglement condition across all turtles. Innis et al. (2010) and Dodge et al. (2014) deliberately included turtles with apparent entanglement injuries in their studies, and an attending veterinarian conducted detailed animal health assessments. Comparable assessments were not available for the sample from Canada. Therefore, it is possible that the results from Canada may reflect biases associated with turtles that, although entangled, appeared relatively healthy at the time of tagging. This is possible because, to meet animal care permitting requirements, only turtles that appeared active and responsive were equipped with satellite tags off Nova Scotia.

The data presented here indicate that some leatherbacks survive entanglement events and complete long-distance migrations. However, opportunistic satellite tagging of entangled leatherbacks is logistically challenging. Therefore, to date, only small sample sizes have been achieved and under inconsistent study protocols. These limitations have precluded quantification of postrelease mortality of leatherbacks following bycatch in various fisheries. Targeted studies of fates of incidentally captured leatherbacks at the time of release and after release are urgently required to effectively quantify the threat of incidental entanglement. Such research should apply standardized protocols for leatherback health assessment and should consider the role of different environmental conditions, gear types, and entanglement severity on fates of turtles. In the interim, survival outcomes for leatherbacks interacting with fisheries could be enhanced through efforts to reduce the duration of entanglement events. This may be accomplished through reduced soak times, regular checking of gear, and implementation of prompt and humane disentanglement protocols.

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