Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/authorsrights

Author's personal copy

Fisheries Research 151 (2014) 114–121

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Movements of dolphinfish (*Coryphaena hippurus*) along the U.S. east coast as determined through mark and recapture data

Wessley Merten[a,*], Richard Appeldoorn[a], Donald Hammond[b]

[a] Department of Marine Sciences, University of Puerto Rico Mayagüez, PO Box 9000, Mayagüez, Puerto Rico 00681, Puerto Rico
[b] Cooperative Science Services LLC, Dolphinfish Research Program, 961 Anchor Road, Charleston, SC 29412, United States

ARTICLE INFO

Article history:
Received 23 March 2013
Received in revised form 23 October 2013
Accepted 28 October 2013

Keywords:
Dolphinfish
Movements
Migrations
Connectivity
U.S. east coast
Mark-recapture

ABSTRACT

Conventional mark and recapture ($n = 306$ recaptures) and satellite monitoring data ($n = 6$ transmitters) were used to examine small and large scale dispersal and movement patterns of dolphinfish (*Coryphaena hippurus*) along the U.S. east coast. Movement rates were dependent upon region, latitude, and distance from shore released. Movements from Florida to the South-Atlantic Bight (SAB) (44.67 ± 39.53 km/d) and Florida to northeastern North Carolina (MAB) (44.62 ± 15.31 km/d) had the highest observed rates, while movements within the SAB were the slowest (11.80 ± 27.94 km/d). Regional movement headings varied with latitude, with dolphinfish released from Florida Keys to Central Florida displaying the most directional variability, with 3.5% conducting southerly movements. The majority of the southerly movements occurred during fall. The maximum straightline dispersal rate was 238.25 km/d and the greatest displacement distance was 1915 km observed in 51 days between the Florida Keys and Long Island, New York. Understanding the movements of dolphinfish along the U.S. east coast is the first step toward better predicting seasonal and annual stock abundances by state and elucidating state-to-state stock connectivity. On a larger scale, identifying movement patterns along the east coast is a pre-requisite to describing the spatial and temporal movement patterns to other regions such as the Bahamas and Caribbean Sea.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Dolphinfish, *Coryphaena hippurus* Linnaeus, 1758, is a highly migratory circum-tropical species (Oxenford, 1999; Hammond, 2008) of significant commercial and recreational importance (Oxenford and Hunte, 1986; Rodríguez-Ferrer et al., 2004). However, there is a lack of information on the movements and migrations of dolphinfish along the U.S. east coast necessary for appropriate stock-based management (Mahon and Oxenford, 1999). Understanding these factors is critically important for both fishers and managers to be able to predict the distribution and occurrence of dolphinfish throughout the year, enhance resource allocation, and conduct more applicable stock assessments.

Along the U.S. east coast, dolphinfish are distributed from George's Bank, off New England, south to Key West, Florida (Beardsley, 1967). Throughout this range, dolphinfish abundances are seasonally variable. Off Florida, abundances increase during April and peak from May to June; in the South Atlantic Bight (SAB), dolphinfish begin to increase during May and peak in abundance during June and July (Oxenford and Hunte, 1986). In the Mid-Atlantic Bight (MAB), abundances begin increasing in June and peak from July to August (Oxenford and Hunte, 1986). Despite knowledge of these patterns, movements connecting successive peaks in abundance in differing regions are lacking and are needed to describe the spatial and temporal extent necessary for regional management (Oxenford and Hunte, 1986).

Past movements of dolphinfish were largely inferred through compiling size and abundance observations at geographically separated locations by time of year (Oxenford and Hunte, 1986; Rivera and Appeldoorn, 2000). However, observations such as these do not uncover regional connectivity patterns, movement pathways, distances covered, and movement rates that dolphinfish actually exhibit while moving along the U.S. east coast. A mark and recapture study conducted in 1991 along the U.S. east coast resulted in 60 marked dolphinfish and only 4 recaptures, which offered little insight into their movements and migrations (Personal Comm. Donald Hammond). From 2002 until 2005, the South Carolina Department of Natural Resources (SCDNR) initiated a larger scale mark and recapture study along the U.S. east coast, which resulted in 4922 marked and released dolphinfish and 125 reported recaptures. These data were the first to show a northerly movement trend along the U.S. east coast from Florida to the MAB and movement rates and patterns between tagging regions (Hammond, 1998). Since 2006, the Dolphinfish Research Program, which started after

---

* Corresponding author. Tel.: +787 436 8300.
E-mail address: wessley.merten@upr.edu (W. Merten).

0165-7836/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fishres.2013.10.021

Author's personal copy

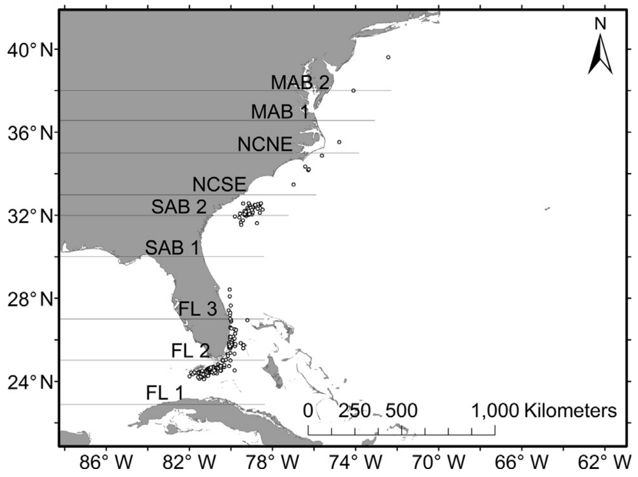

Fig. 1. Dolphinfish tagging zones and subzones along the U.S. east coast are separated by their southern and northern latitude limits. White circles represent tagging locations for all dolphinfish marked and recaptured along the U.S. east coast.

the termination of the SCDNR study, has marked and released an additional 9524 dolphinfish from along the U.S. east coast, Bahamas, and Caribbean Sea, resulting in 287 additional recaptures over small and large spatiotemporal scales.

This paper describes the movements and migrations of dolphinfish along the U.S. east coast utilizing dolphinfish mark and recapture data from 2002 until 2011. The main objective was to quantify dolphinfish movements and dispersal rates within and among regions along the U.S. east coast. Secondary objectives were to investigate movements relative to coastal geomorphology, bathymetry, association with *Sargassum*, and fluctuations in the North Atlantic Oscillation (NOA). Lastly, results were compared to movements of dolphinfish released with pop-up satellite archival transmitters (PSATs) to assess if there was bias in resulting headings from the use of fishery-dependent data, and to surface drifters to see if movements approximated the movement of surface currents. Results were used to identify knowledge gaps and priority research areas and to discuss larger scale basin-wide dolphinfish movements and migrations around the western north Atlantic.

2. Materials and methods

2.1. Conventional mark and recapture data

Conventional dolphinfish mark and recapture data were provided by the Dolphinfish Research Program (DRP) from 2002 until 2011 along the U.S. east coast. All release and recapture events were reported by recreational, sport, and commercial fisherman participating in the program from different locations along the east coast. Anecdotally, the movement patterns of-dolphinfish along the east coast is thought to vary between regions. Therefore, data were pooled relative to four main tagging zones, Florida (FL), the South Atlantic Bight (SAB), North Carolina (NC), and the Mid-Atlantic Bight (MAB), which were further broken down into 9 subzones based on latitude and fishing pressure relative to tagging effort to examine differences in movement patterns (Fig. 1). Hallprint® PDAT nylon dart tags (Hallprint, South Australia, Australia) were used, each with an individually numbered external 15.2 cm yellow or orange polyethylene streamer. Tags were implanted in the dorsal musculature posterior the operculum below the base of the dorsal fin. Reported data were filtered for misreported or absent information such as mark and recapture dates or geographic positions. After filtering, coupled release and recapture events were spatially analyzed using ArcGIS 10.0.

2.2. Satellite tagging data

Pop-up satellite archival transmitter (PSAT) data were provided by the Dolphinfish Research Program from 2005 to 2011. Six dolphinfish (5 male, 1 female) were tagged and released along the U.S. east coast. All fish were tagged with Microwave Telemetry Inc., pop-up satellite archival transmitters (PSAT PTT-100 standard (180 d; $n = 1$), and high-rate x-tag models (30 d; $n = 5$); Microwave Telemetry Inc., Columbia, MD, USA). Pop-up locations were estimated by Argos© using the Least squares analysis algorithm. Each PSAT was attached to a stainless steel internal anchor dart (16 mm × 50 mm) using monofilament and a brass crimp to secure a loop through the wire attachment point on the top of the device. The tag was then secured in the dorsal musculature of the fish using the anchor dart and a 2 m tagging pole, or by inserting a 254 mm long section of 1.6 mm diameter monofilament laterally through the dorsal musculature from one side to the other. On the exiting line, a stainless steel plate (8 mm × 25 mm) was secured using a brass crimp to form a stopper-loop. Dolphinfish were caught using traditional offshore pole and troll techniques using bait (fresh ballyhoo) and 7.0 circle hooks. Dolphinfish qualifying for tagging were required to be a minimum of 95 cm FL, be lip-hooked, and visually healthy. Two methods of tag attachment were utilized. One method allowed the fish to remain in the water while the other brought the fish onboard in a large net. In both instances, the tag was inserted into the dorsal musculature about one-third of the fish's length behind the head. While onboard, the fish was calmed by placing a wet towel over its eyes and inserting a hose carrying fresh ocean water into its mouth in an attempt to provide oxygen until it was returned to the water. Fish were returned to the water within two minutes and monitored for two more minutes before the hook was removed and the fish was released.

2.3. Spatial analysis

Straight-line distances, headings (0° = true north), minimum distance from shore (DFS), and distance from the 200-m isobath, were obtained between all release and recapture events using ArcGIS 10.0. The 200-m isobath was used to represent the edge of the continental shelf. Spatial data for the shoreline and 200-m isobath were obtained from the National Oceanic and Atmospheric Administration's National Geophysical Data Center[1] (NGDC) and Coastal Services Center,[2] respectively.

2.4. Data analysis

Dispersal rates (km/d) were calculated according to distance and days at liberty (DAL) between release and recapture events and log-transformed to normalize their distribution. Movements were categorized relative to 14 different dispersal patterns to assess regional connectivity between zones and subzones (Table 1). These different patterns represented dolphinfish movements between 2 and 119 DAL ($n = 229$). Excluded from the analysis were fish at liberty from 0 to 1 days (to rule out the stress of tagging), fish at liberty from ≥120 days (to exclude potential roundtrips through the Bahamas or beyond), fish recaptured in international waters, and fish that had southerly headings (analyzed separately). In addition, using these data, northerly movements within zones were calculated. To analyze differences of northerly movement rates with increasing latitude, rates between release and recapture events

---

[1] accessed January 2012: http://www.ngdc.noaa.gov/mgg/shorelines/data/gshhs/.

[2] accessed January 2012 http://ocean.floridamarine.org/efh_coral/ims/dbGroupTOC/metadata/Continental%20Shelf.htm.

Author's personal copy

Table 1
Comparisons of average (km/d) dispersal rates among and between zones for dolphinfish at liberty from 2 to 119 days moving north ($n = 229$) and south ($n = 6$) along the U.S. east coast.

Dispersal type	N	Rate	
		Average (km/d)	Standard deviation
Florida Instate	114	33.92	28.29
Florida to SAB	4	44.67	39.53
Florida to NCSE	31	37.63	21.13
Florida to NCNE	10	44.62	15.31
Florida to MAB	11	41.86	35.60
SAB within zone	11	11.80	27.94
SAB to NCSE	22	19.99	21.89
SAB to NCNE	13	20.34	13.23
NCSE within zone	3	21.36	10.55
NCSE to NCNE	1	7.20	N/A
NCNE within zone	1	4.32	N/A
SAB to MAB	7	16.85	11.92
MAB within zone	1	9.84	N/A
Florida to the South	6	10.36	6.76

from 2 to 119 DAL ($n = 229$) were log-transformed and a regression analysis performed.

The non-parametric alternative of an analysis of variance (ANOVA), the Kruskal–Wallis test, was used to examine differences of northerly movements and dispersal rate within and between zones. Pairwise comparisons of northerly movement and dispersal rates within and between zones were tested using the non-parametric Mann–Whitney test. In addition, the Kruskal–Wallis and Mann–Whitney tests were used to analyze whether *Sargassum* presence or absence during release and recapture events ($n = 127$) of dolphinfish significantly affected northerly dispersal rate. Linear regressions were used to examine northerly dispersal rates relative to distance from shore (DFS) between Florida and SAB tagging zones ($n = 229$). In addition, Mann–Whitney pairwise comparisons of dolphinfish released inshore and offshore of the 200-m isobath in Florida and SAB were conducted. Lastly, a Mann–Whitney pairwise test was used to determine if size (FL = fork-length) affects dispersal rate. Dolphinfish were categorized relative to small (<50 cm) and large (>50 cm) sizes, and dispersal rates between groups were compared.

Dolphinfish mark and recapture results were pooled by zone and subzone, relative to northerly movement headings, and Mann–Whitney pairwise comparisons were applied to examine differences in average movement directions and rates between zones. Excluded from the pairwise comparisons of dispersal rate between zones were dolphinfish moving within NCSE ($n = 3$), between NCSE and NCNE ($n = 1$), within NCNE ($n = 1$), and within MAB ($n = 1$) due to low sample size. Dolphinfish tagged with pop-up satellite archival transmitters (PSATs) ($n = 6$) provided an opportunity to examine fishery independent movements of dolphinfish. Average direction and rate from conventionally and PSAT tagged fish were compared using Mann–Whitney pairwise comparisons. Movement headings and average dispersal rates were then compared using the same analyses against surface drifters ($n = 14$; see below) using ArcGIS 10.0.

2.5. Comparisons to surface drifters

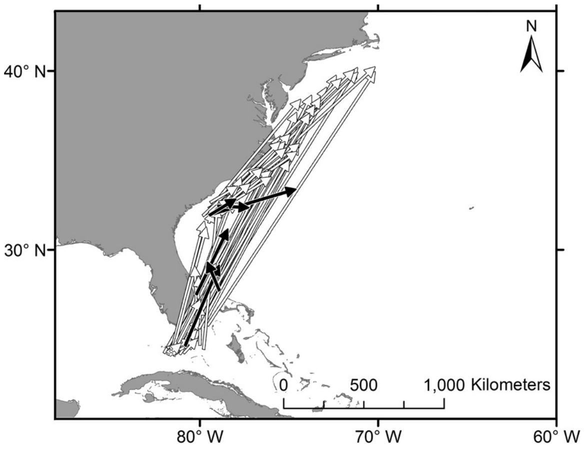

Fig. 2. Straight-line dolphinfish dispersal movements along the U.S. east coast. White arrows ($n = 55$) indicate conventional mark and recapture data while black arrows represent pop-up satellite archival transmitter movements between tagging and pop-up locations ($n = 6$) (see also Table 6).

To test if dolphinfish movements were different from general current flow, comparisons were made between tagging results and movements of surface drifters. Surface drifter tracks were obtained courtesy of Prof. R. H. Weisberg and the University of South Florida Ocean Circulation Group. A total of 23 drifter tracks were used from the origin of the Florida current (24°N × 81°W) and moving north along the eastern Florida shelf up to the MAB (Liu et al., 2011a,b). Log-transformed average surface drifter velocities were examined relative to log-transformed dolphinfish dispersal rates from Florida tagging zones, i.e., Florida in-state, Florida to the SAB, and Florida to the MAB, using the Mann–Whitney pairwise test. In addition, mark and recapture events that occurred within the drifter deployment time frames ($n = 3$) were compared relative to dispersal rate and trajectory. Additionally, southerly dispersal rates along the eastern Florida shelf were compared to surface drifter rates using a Mann–Whitney pairwise test. Lastly, log transformed dolphinfish dispersal rates from the SAB and NCSE ($n = 59$) were compared to fluctuations in the position of the Gulf Stream relative to changes in the North Atlantic Oscillation (NAO) using a Kruskal–Wallis test.

3. Results

3.1. Conventional mark and recapture data

A total of 306 dolphinfish (25–130 cm FL; 2–119 DAL) were recaptured by fishermen participating in this study along the U.S. east coast from 2002 to 2011.

This represents an overall recapture rate of 2.2%. Overall, 76% of recaptures originated from Florida, followed by 23% from the SAB, and 0.65% from the MAB. Average dispersal rate for all dolphinfish marked and recaptured along the U.S. east coast, regardless of days at liberty, was 34.06 ± 34.80 km/d (mean ± standard deviation [SD]). Straight-line dispersal movements and DAL ranged from 0.71 to 1915.09 km and 0 to 325, respectively.

Conventional marked ($n = 229$) and satellite tracked ($n = 6$) dolphinfish between 2 and 119 DAL moved broadly to the north along the continental shelf of the U.S. east coast (Fig. 2). Mark and release locations relative to distance from shore, and the 200-m isobath, varied significantly between Florida and the SAB (Mann–Whitney; $P < .001$). Florida dolphinfish were released both closer to shore (24.38 ± 14.51 km) and the 200-m isobath (9.09 ± 10.99 km) than SAB released dolphinfish (shoreline 85.91 ± 21.51 km and 200-m isobath 15.08 ± 13.44 km). The 200-m isobath ranges closer to shore along Florida zones (5–55 km) than within SAB zones (88–124 km). Dolphinfish were caught more frequently inshore of the 200-m isobath within SAB zones (85%; $n = 53$) than Florida (48%; $n = 87$). In Florida, most dolphinfish were released within 10 km (67%; $n = 115$) of the 200-m isobath, while in the SAB, most were released within 15 km (67%; $n = 40$).

Movements along the U.S. east coast, as categorized into the fourteen regional patterns, are given in Table 1. Most recaptures occurred within the region in which tagging took place.

Author's personal copy

Table 2
Comparisons of average movement rates (km/d) and regional trajectories (whole-circle bearings with 0° = true north) by zone for dolphinfish ranging from 2 to 119 days at liberty (DAL) along the U.S. east coast. The pooled movement average, variance, and standard deviation across all zones are provided. (Florida tagging zones = 23–30°N; South Atlantic Bight (SAB) tagging zones = 30–33°N; North Carolina to Virginia (NC) tagging zones = 33–36.5°N, Mid-Atlantic Bight (MAB) tagging zones ≥ 36.5°N).

Tagging zone and subzone	*N*	Average rate (km/d)	Trajectory mean (°) ± SD
(FL 1) – FL Straits = 23–25°N			54.14 ± 29.78
Key West	35	35.04	
Big Pine Key	30	39.12	
Marathon	39	39.84	
Islamorada	13	36.24	
(FL 2) – FL Central = 25–27°N			10.50 ± 10.94
Key Largo to Biscayne Bay	9	38.40	
Miami	26	27.60	
Ft. Lauderdale	7	36.96	
Boynton Beach to Jupiter	4	51.12	
(FL 3) – FL North = 27–30°N			304.37 ± 100.89
Jupiter to Cape Canaveral	6	13.2	
(SAB 1) – Savannah, GA = 30–32°N	9	38.64	38.12 ± 9.54
(SAB 2) – Charleston, SC = 32–33°N	45	15.36	43.92 ± 19.71
(NCSE) – Wilmington, to Hatteras Bight, NC = 33–35°N	5	14.16	68.62 ± 100.67
(NCNE) – Hatteras Bight, NC, to SE Virginia Beach, VA = 35–36.5°N	0	N/A	N/A
(MAB 1) – Virginia to Maryland = 36.5–38°N	1	10.08	34.33
(MAB 2) – Maryland to Massachusetts ≥ 38°N	0	N/A	N/A
All dolphinfish 2–119 DAL	229		
Pooled average (km/d)		31.24	
Standard deviation		27.11	

Table 3
Mann–Whitney pairwise comparisons of northerly dispersal movements (2–119 DAL) and rates (km/h) within and between zones along the U.S. east coast ($n = 223$). Bolded and underlined numbers indicate significance at the $P < .05$ level.

Dispersal movements and zone	FL Inst.	FL to SAB	FL to NCSE	FL to NCNE	FL to MAB	SAB Inst.	SAB to NC SE	SAB to NC NE	SAB to MAB
FL Inst.	–	0.481	0.168	0.103	0.396	**0.000**	0.067	0.270	0.251
FL to SAB		–	0.959	0.572	0.896	**0.013**	0.076	0.213	0.131
FL to NCSE			–	0.154	0.764	**0.000**	**0.000**	**0.005**	**0.004**
FL to NCNE				–	0.181	**0.002**	**0.001**	**0.003**	**0.002**
FL to MAB					–	**0.001**	**0.006**	0.052	**0.013**
SAB Inst.						–	**0.002**	**0.002**	**0.010**
SAB to NCSE						–	0.339	0.959	
SAB to NCNE							–	0.843	
SAB to MAB								–	

In-state and within-zone (Florida and SAB) movements constituted 64% of dolphinfish recaptures, and dispersal rates varied significantly between zones and subzones (Kruskal–Wallis; $P < .001$). The average northerly rates between zones and subzones are given in Table 2. Pairwise comparisons of dispersal rate relative to dispersal pattern by zone are presented in Table 3.

Northerly rates decreased significantly ($P < .001$) from south (23°N) to north (33°N), but this trend only explained 10% of the variability in differences in dispersal rate ($n = 229$) ($r^2 = .101$). Distance released from shore did not significantly affect northerly dispersal rate within Florida. However, northerly dispersal rate increased significantly ($P = .003$) the further dolphinfish were released from shore in the South Atlantic Bight (SAB) ($n = 59$) ($r^2 = .143$). In the SAB, there was a significant difference in northerly dispersal rate for dolphinfish released closer to shore (<100 km) (13.50 ± 10.90 km/d; $n = 45$) than further from shore (>100 km) (34.61 ± 37.74 km/d; $n = 14$) (Mann–Whitney; $P = .040$). There were no significant differences in northerly dolphinfish dispersal rate ($n = 65$) from the SAB and NCSE tagging zones relative to fluctuations in the Gulf Stream affected by changes in the North Atlantic Oscillation. Overall, rate ($n = 127$) was not affected by the presence of *Sargassum*. However, there was a significant difference in dispersal rate relative to *Sargassum* being absent during release but present during recapture (42.13 ± 31.48 km/d) versus present during release and absent during recapture (25.18 ± 27.20 km/d) (Mann–Whitney; $P = .019$) and present during both events (29.43 ± 26.82 km/d) (Mann–Whitney; $P = .058$) (Table 4). Pairwise comparisons of size versus dispersal rate showed no significant differences in dispersal rate.

Regional northerly headings (Table 2) varied significantly with latitude by zone (Krustal–Wallis; $P < 0.001$) and subzone (Mann–Whitney; $P < 0.001$). Along the Florida Keys (FL1), headings ranged from E-NE, while along central and northern Florida (FL2-FL3) dolphinfish headed NNE-NNW; in the South Atlantic Bight (SAB1-NCSE), dolphinfish moved NE.

For all recaptures, 8.2% had southerly headings between mark and recapture locations. However, 66.6% ($n = 12$) of these were considered lingering movements and were not classified as southerly movements. Southerly movements for dolphinfish released off of Florida ($n = 6$) (Fig. 3) averaged 10.36 km/d (Table 5). All southerly movements except one were initiated and terminated within 15 km

Table 4
Mann–Whitney pairwise comparisons of rate (km/d) and *Sargassum* presence and absence during tagging and recapture events for dolphinfish moving north along the U.S. east coast are presented in the table below ($n = 127$) (AA = absent, absent ($n = 5$); AP = absent, present ($n = 27$); PA = present, absent ($n = 20$); PP = present, present ($n = 75$)). Bolded numbers indicate significance at the $P = .05$ level.

Sargassum presence/absence and dispersal rate	AA	AP	PA	PP
AA	–	0.856 ($n = 32$)	0.497 ($n = 25$)	0.585 ($n = 80$)
AP		–	**0.035** ($n = 47$)	**0.058** ($n = 102$)
PA			–	0.514 ($n = 95$)
PP				–

Author's personal copy

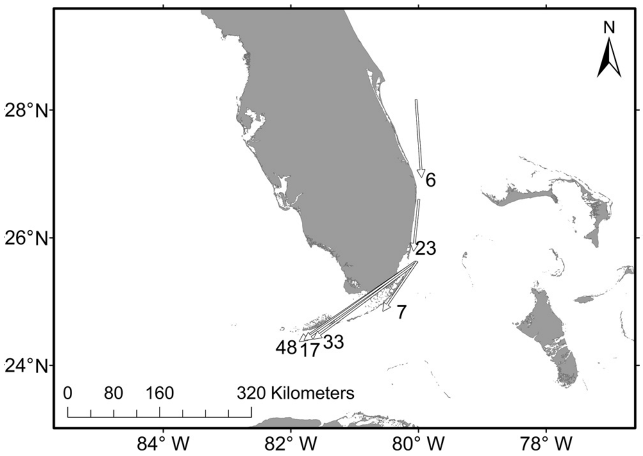

Fig. 3. Southerly movements for 6 dolphinfish marked and recaptured along the eastern Florida shelf from 2005 to 2011. The numbers next to the arrows correspond to days at liberty between mark and recapture locations.

of the coastline. The exception was the shortest DAL (6 DAL). This fish was released 48.56 km from shore and was recaptured only 8.39 km from shore, representing a southerly movement from offshore of Palm Bay to Jupiter Inlet. Among the other southerly movements there were three instances of a dolphinfish moving south from Miami to Key West, an approximate distance of 241 km. These three fish were at liberty from 17 to 48 days and averaged moving 7.86 km/d. Southerly movements occurred along eastern Florida shelf between fall ($n = 4$; October–December) and spring ($n = 3$; March–May). The longest southerly displacement took place in December, with the following three longest displacements occurring in March, November, and May, respectively. Southerly movements from Miami to the Florida Keys occurred most often during the fall with only one movement occurring during the spring.

3.2. *Satellite tagging data*

Between 2005 and 2010, six dolphinfish (97.5–112.5 FL) were tagged and monitored with pop-up satellite archival transmitters (PSATs) ranging from 2.5 to 10 DAL (Table 6). All transmitters surfaced prematurely (2.54–10.08 d). Maximum straightline distances ranged from 122 to 559 km with dispersal rates ranging from 33.98 to 168.15 km/d off Florida ($n = 3$) and 16.85 to 48.59 km/d in the SAB ($n = 3$). These dispersal rates did not vary significantly between regions or when compared to conventional mark and recapture dispersal rates from Florida or the SAB. When compared to Florida south, Florida North, and SAB conventional mark and recapture data, regions from which PSATs were deployed, there were no significant differences in initial trajectories between zones but there was a significant difference within the SAB (Mann–Whitney; $P = .038$), with PSATs ($n = 3$) averaging 72.24° while conventional mark and recapture movements averaged heading 46.71° ($n = 54$).

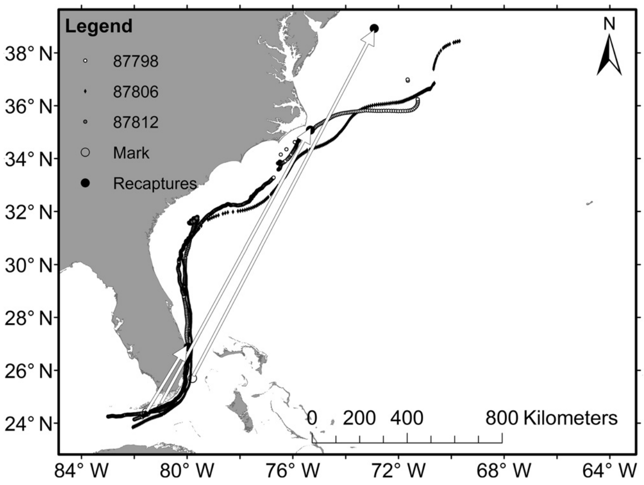

Fig. 4. Surface drifters deployed in 2010 closely followed surface currents along the U.S. east coast from the Florida Straits to the Mid-Atlantic Bight. Mark and recapture events that occurred within the drifter track deployment time frames are displayed above (Drifter tracks obtained courtesy of Prof. R.H. Weisberg and the University of South Florida Ocean Circulation Group).

3.3. *Comparisons to surface drifters*

There were significant differences in Florida-instate surface drifter rate (69.80 ± 30.77 km/d) versus dolphinfish rate (46.05 ± 60.75 km/d) (Mann–Whitney; $P < .001$), Florida-SAB surface drifter rate (75.54 ± 41.24 km/d) versus dolphinfish rate (37.30 ± 23.27 km/d) (Mann–Whitney; $P < .001$), and between Florida-MAB surface drifter rate (66.60 ± 31.52 km/d) versus dolphinfish rate (44.73 ± 26.95 km/d) (Mann–Whitney; $P < .001$) (Table 7). Comparisons of mark and recapture event locations that occurred within surface drifter deployment periods ($n = 3$) were in good agreement with surface drifter trajectories along the U.S. east coast; however, dolphinfish dispersal rates were substantially lower (17–65%) than drifter dispersal rates (Fig. 4). During 2010, two surface drifters deployed in the Florida Straits moved south for 5 days for 98 and 119 km at 16.56 and 20.53 km/d within 15 km of the coastline. These rates and distances from the shoreline are comparable to the rates and distance from shore of dolphinfish that moved south along the eastern Florida shelf. Both southerly surface drifter trajectories were initiated close to the coastline (<9 km and <18 km) and did not move further offshore until passing Key West.

4. Discussion

Dolphinfish recaptures along the U.S. east coast constituted 88.1% of all recaptures recorded in the western North Atlantic since 2002, a percentage likely attributed to the high fishing effort and strong seasonality associated with the fishery. Here, the use of conventional mark and recapture data, satellite transmitters, and surface drifters highlighted both fine and broad scale movements,

Table 5
Southerly dolphinfish movements along the eastern Florida shelf are provided below. Tag and recapture nearest features are based on the proximity of each event to the nearest landmark. DAL = Days at liberty.

Tag #	Tag ID	Month tagged	Month recaptured	Year	DAL	Distance (km)	Rate (km/d)	Tag nearest feature	Recap nearest feature
1	K041426	5	5	2005	6	126.29	21.12	Palm Bay	Jupiter Inlet
2	X18538	11	11	2011	7	105.49	15.07	Miami	Islamorada
3	X13756	3	3	2011	17	253.87	14.93	Miami	Key West
4	X04042	12	1	2007	23	84.76	3.69	Lantana	Miami
5	X18537	11	12	2011	33	241.48	7.32	Miami	Key West
6	X13019	12	1	2009	48	256.66	5.35	Miami	Key West

Author's personal copy

Table 6
Pop-up satellite archival transmitter (PSAT) monitoring period data obtained from dolphinfish monitored along the U.S. east coast from 2005 until 2011 (ordered from release location; North to South).

Tagging date (mm.dd.yyyy)	Fork length (cm)[a]	Sex	Monitoring period (days)[b]	Tag region	Pop-up region	Direction (°)	Distance (km)	Rate (km/d)
5.1.2010	107.5	F	9.33	SAB	SAB	70.01	453.43	48.59
6.4.2005	107.5	M	8.88	SAB	SAB	53.49	146.84	16.53
6.21.2006	105.0	M	5.83	SAB	SAB	93.22	162.99	27.95
4.23.2010	95.0	M	2.54	Florida North	SAB	22.17	427.22	168.15
5.7.2010	97.5	M	4.96	Florida North	Florida North	341.47	168.59	33.98
5.10.2006	112.5	M	10.08	Florida Straits	Florida North	33.75	543.94	53.96

[a] Estimated fork length.
[b] Days monitoring dolphinfish.

average rates, regional differences, and directionality. This analysis is cornerstone in setting up future discussions of larger basin-wide movements around the western central Atlantic.

4.1. U.S. east coast movement rates

Dolphinfish movements along the U.S east coast occurred at different temporal and spatial scales. On average, dolphinfish were able to travel from Florida to the MAB, an approximate straight-line distance of 1500 km, in just under two months (44.35 ± 23.93 days); movements between Florida and the SAB were slightly less (39.88 ± 23.20 days), but with an approximate straigthline distance of 700 km. The fastest observed movements between these zones occurred within 19 and 6 days, respectively. The observed average time needed to move among regions were in good agreement with the timing of arrival of seasonal dolphinfish abundances along the east coast; annually, peak abundances occur a month apart beginning off Florida during May to June, in the South Atlantic Bight (SAB) from June to July, and in the Mid-Atlantic Bight (MAB) from July to August (Oxenford and Hunte, 1986).

Northerly rates of dolphinfish along the U.S. east coast declined with increasing latitude. Florida dolphinfish may be subject to greater northerly current velocities than those in the SAB due to the increased speed of the Florida Current traveling north through the narrow Florida Straits (Lee et al., 1991). When comparing Florida in-state surface drifter rates to Florida in-state dolphinfish movements, surface drifter rates were significantly faster than dolphinfish movements, possibly due in part to heightened surface current velocities. As dolphinfish travel north along the U.S. east coast, the width of the Florida Current increases from 80 km at 27°N to 120 km at 29°N and continues to widen until it is deflected offshore near 32°N, just upstream of the Charleston Bump (31.38°N × 79.07°W) at the beginning of the Gulf Stream (Olson et al., 1983). This change in continental shelf geomorphology may explain in part why changes in northerly dolphinfish dispersal rate were most pronounced in the SAB i.e. slower, than off Florida. The difference may be due to the presence of the Charleston Bump rising up from the Blake Plateau causing onshore meanders, eddies, and the cyclonic Charleston Gyre to form based on the trajectory and seasonality of the Florida

Table 7
Surface drifter and dolphinfish distances, rates, and movements between tagging zones are provided below. Bolded drifter and fish ID numbers indicate that they were used in Fig. 4. (Drifter data obtained courtesy of Prof. R.H. Weisberg and the University of South Florida Ocean Circulation Group).

Drifter ID	Start date	End date	Distance (km)	Rate (km/d)	Movement	
					Start zone	End zone
87797	7/1/2010	7/18/2010	445.01	26.17	FL 1	FL 3
87798	7/8/2010	8/9/2010	1734.48	54.96	FL 1	MAB
	7/8/2010	8/6/2010	1423.92	49.81	FL 1	NCNE
	7/8/2010	7/25/2010	951.66	57.96	FL 1	SAB
	7/8/2010	7/18/2010	579.04	55.68	FL 1	FL 3
87802	7/16/2010	7/27/2010	677.55	64.52	FL 1	FL 3
87806	9/3/2010	9/21/2010	1999.82	111.36	FL 1	MAB
	9/3/2010	9/14/2010	1293.51	118.04	FL 1	NCSE
	9/3/2010	9/12/2010	967.12	112.08	FL 1	SAB 2
	9/3/2010	9/9/2010	639.47	110.4	FL 1	FL 3
87812	8/4/2010	8/18/2010	873.21	66.99	FL 1	SAB 1
	8/4/2010	8/12/2010	582.43	75.12	FL 1	FL 3
38836	6/20/2010	6/27/2010	663.27	107.52	FL 1	FL 3
87795	8/6/2010	8/15/2010	393.09	47.4	FL 1	FL 2
	7/19/2010	7/25/2010	98.00	16.56[a]	FL 2	FL 1
87796	7/17/2010	7/23/2010	119.75	20.53[a]	FL 1	FL 1
22456	8/8/2003	8/13/2003	787.77	157.55	FL 2	SAB
39763	9/21/2003	10/11/2003	1014.26	50.71	FL 1	SAB
39765	9/14/2003	11/3/2003	1907.37	38.15	FL 1	SAB
	9/14/2003	10/14/2003	977.97	32.59	FL 1	SAB
39766	12/23/2003	1/12/2004	917.00	45.85	FL 1	SAB
20274	9/24/2003	10/24/2003	1869.12	62.30	FL 1	MAB
	9/24/2003	10/4/2003	830.70	83.07	FL 1	SAB
Fish ID	Tag date	Recap date	Distance (km)	Rate (km/d)	Movement	
					Start zone	End zone
X15782	7/9/2010	11/10/2010	316.28	2.55	FL 1	FL 3
X11978	7/10/2010	8/10/2010	1289.71	41.60	FL 1	NCSE
X11502	6/3/2010	8/11/2010	1602.94	23.22	FL 2	MAB 2

[a] Southerly movement.

Author's personal copy

Current and Gulf Stream (Lee et al., 1991; Schmeits and Dijkstra, 2001).

4.2. Distance from shore and the Charleston Gyre affect

Northerly dispersal rates from the SAB were significantly lower than rates from Florida. Conditions for meander and eddy formation occur periodically each summer along the Florida/Georgia shelf where eddies form upstream of Cape Canaveral with diameters of 10–30 km, durations of 2–14 days, and northerly velocities of 4.32 km/d. It is likely that these features, along with the cyclonic Charleston Gyre, which has been observed to be present 65% of the time throughout any given year in the SAB region (Lee et al., 1991), may suppress the northerly rates of dolphinfish moving along this portion of the east coast. Within the time period of this study, surface drifters were observed to get absorbed in these features while moving northeast within the SAB, which suggests that dolphinfish may also become absorbed in these features, too. For example, two dolphinfish were marked and recaptured off of Charleston, South Carolina, after only moving 30.54 and 105.90 km to the north in 70 and 77 days, respectively. Both fish were released inside of the break in the continental shelf and within 90 km of the coastline.

In the SAB, dolphinfish dispersal rates increased when released further from shore. The 200-m isobath, used as a reference to the break in the continental shelf, averages 85 km from shore in the SAB. Therefore, dolphinfish released inshore of this feature are presumably under the influence of the Charleston Gyre, while fish released further offshore are not. This may explain why dolphinfish northerly rates from the SAB within 100 km of the coastline are more than two times less (13.50 ± 10.90 km/d) than dolphinfish northerly rates released beyond 100 km (34.61 ± 37.74 km/d). Current dynamics in the SAB vary throughout the year, in part in response to changes in the position of the Gulf Stream, which responds to fluctuations in the NAO between a positive and negative phase (Coëtlogon et al., 2006). As a result, dolphinfish rates released inshore or offshore of the 200-m isobath should vary by year and strength of the NAO. However, there were no significant differences in movement rates relative to changes in the NAO during the study period, relative to distance from shore, but this could be due to sample size between years and merits future investigation.

4.3. Object fidelity

The presence of *Sargassum* revealed a pairwise relationship with northerly rate along the east coast. Dolphinfish have been shown to exhibit strong fidelity with *Sargassum* and other floating objects on the open ocean (Hemphill, 2005). *Sargassum* is distributed within the tropical oceans of the world and is known to occur along the eastern Florida shelf and in the SAB (Hu, 2009). When *Sargassum* was absent then present, versus present then absent or present/present, during release and recapture events, there was a significant increase in northerly rate. This result seems counter to expectations because fish initially caught with *Sargassum* would be expected to move more rapidly according to drifter data. The cause for this incongruity is unknown but possible explanations could be related to fish behavior or sampling (fishing) bias. Dolphinfish have been observed to remain with drifting fish-aggregating devices (dFADs) for as much as 14 days (Taquet et al., 2007). However, not reported in that study were object-fidelity relative to drifter rate or drifter distance covered, fidelity with different drifting objects that vary in size and shape, movements between dFADs (object-skipping), or behavior with an object in a major western boundary current like the Gulf Stream. Sampling bias could be an explanation due to the variability in seasonal prevalence of *Sargassum* and the distance from port fisherman need to or are willing to travel by region along the U.S. east coast.

4.4. Directionality

Northerly movement headings varied significantly between zones and subzones along the U.S. east coast. Headings were wider ranging in the Florida Keys than along central and northern Florida and the SAB but largely followed the geomorphology of the coastline and subsequent current flow. In addition, movement headings of PSAT tagged dolphinfish were in good agreement with conventionally marked and released fish off Florida, but varied significantly when compared to average heading in the SAB. Satellite monitored dolphinfish moved further east offshore, which could represent the true movements of dolphinfish in this region but were unseen in mark and recapture data due to the concentrated fishing effort along the continental shelf break and a reluctance to fish further offshore. Pop-up locations for two of the three PSATs were outside of the general location of recaptures in the SAB. Estimates for pop-up locations were provided by Argos using the Least squares analysis algorithm; due to the type of transmitters used and nature of this study, geolocation tracks were not calculated or needed to verify a northerly movement trend. Both satellite and conventionally marked dolphinfish had northerly movement components that coincided with large scale current movements along the U.S. east coast, such as the Gulf Stream, and were confirmed in the headings obtained from surface drifters whose monitoring periods overlapped with mark and recapture data.

Southerly movements constituted a small but important portion of all dolphinfish dispersals in this study. Southerly movements were initiated only within the Florida tagging zone. Along the nearshore portion of the eastern Florida shelf a southerly countercurrent is present during the fall and winter months (Düing and Johnson, 1971; Lee et al., 1991; Soloviev and Wood, 2011). All of the southerly movements observed by dolphinfish from 2002 until 2011 at liberty between 6 and 48 days were initiated inshore of the influence of the Florida Current and within the portion of the coastline that experiences the seasonal Florida coastal countercurrent (Düing and Johnson, 1971; Soloviev and Wood, 2011). Of the 6 southerly movements observed along the coast of Florida, the longest occurred during 2009, when the coastal countercurrent had its' strongest southerly mean transport of 155.74 m^3/s (Düing and Johnson, 1971; Soloviev and Wood, 2011). While these examples of southerly movements did not overlap in time with southerly surface drifter tracks, the fact that southerly surface drifter tracks do occur confirms the periodic occurrence of southerly nearshore counter-currents in the Florida Straits, and these could lead to and facilitate southerly dolphinfish movements.

4.5. Management

These results advance our understanding of the spatial and temporal scale of movements and regional connectivity of dolphinfish moving along the U.S. east coast. At present, dolphinfish within US waters are managed under the Dolphinfish/Wahoo Fishery Management Plan (FMP), a multijurisdictional approach led by the South Atlantic Fishery Management Council. This plan recognizes the movement of dolphinfish along the east coast (hence the multijurisdictional approach), but only based on the regional timing of arrival of dolphinfish stocks along the coast by using historical seasonal abundances collected at geographically separated locations such as Florida, South Carolina, and North Carolina (Oxenford, 1999). The present study enhances this view by confirming that the apparent coastal migration indeed consists of the individual movements of fish along the coast, as opposed, for example, to a sequential movement of fish between offshore and

Author's personal copy

inshore locations. Within a management context, movement rates and pathways can be used to more accurately assess the annual and seasonal variability in timing of arrival, duration present, and departure of fish along the U.S. east coast. These estimates of rate, distance and direction, thus can be used to refine stock assessments because estimates of fishing mortality could now be partitioned over space and time according to the particular subgroup of fish actually being targeted.

Overall, these data can be used to assess variations in seasonal and annual movements along the coast relative to currents and other oceanographic patterns, including annual variability in strength and trajectory of the Gulf Stream. Different factors may affect basin-wide movements, such as the role of currents, large-scale meteorological cycles such as the NAO, and annual differences in ocean temperature and salinity. From this perspective, while this study elucidates the general movement of dolphinfish along the U.S east coast, it does not integrate that into a complete picture of dolphinfish migrations around the western North Atlantic. Such a view is necessary for understanding stock structure and basin-wide connectivity of dolphinfish and perhaps other factors affecting growth, reproduction and mortality, which could then translate into significant changes in basin-wide stock assessments and management. Climate change introduces different scenarios for dolphinfish movements given the general consensus that ocean current rates could slow and shift as a result of changing global thermohaline circulation (Latiff et al., 2006). Changes in current rates may or may not affect the rate of movements along the U.S. east coast depending on the underlying driving factors, given that dolphinfish in this study moved at a slower rate than current drifters. However, changes in movement rates could affect dispersal to areas and regions such as the Outer Banks of North Carolina, Bermuda, the Bahamas, and the Caribbean Sea.

Acknowledgements

This research was supported by funding through the Marine Resources Division of the South Carolina Department of Natural Resources and the Cooperative Science Services, LLC., Dolphinfish Research Program. We would like to thank all of the recreational, charter, and commercial fisherman, and all of the businesses, organizations, and individuals for their financial support making this study possible. Their dedication to the advancement of our understanding of the movements and life history of dolphinfish is gratefully acknowledged. Thanks to Roberto Rivera for insight into statistical approaches, Julio Morell for oceanographic advice, and an anonymous reviewer who provided helpful comments on early drafts of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2013.10.021. These data include Google maps of the most important areas described in this article.

References

Beardsley, G.L., 1967. Age, growth, and reproduction of the dolphin, *Coryphaena hippurus*, in the Straits of Florida. Copeia 2, 441–451.

Coëtlogon, G.D., Frankignoul, C., Bentsen, M., Delon, C., Haak, H., Masina, S., Paradaens, A., 2006. Gulf stream variability in five oceanic general circulation models. J. Phys. Oceanogr. 36, 1235–2119.

Düing, W., Johnson, D., 1971. Southward Flow under the Florida Current. Science 173 (3995), 428–430.

Hammond, D.L., 1998. South Carolina Recreational Dolphin Fishery. South Carolina Department of Natural Resources Special Report, pp. 14p.

Hammond, D., 2008. Using pop-off satellite archival tags to monitor and track dolphinfish and cobia, Available online http://dolphintagging.homestead.com/2007SatelliteTagCompletionRpt.pdf

Hemphill, H., 2005. High seas marine protected areas: conservation on the high Seas – drift algae habitat as an open ocean cornerstone. Parks 15, 48–56.

Hu, C., 2009. A novel ocean color index to detect floating algae in the global oceans. Remote Sens. Environ. 113, 2118–2129.

Latiff, M., Böning, C., Willerbrand, J., Biastoch, A., Dengg, J., Keenlyside, N., Schweckendiek, U., 2006. Is the thermohaline circulation changing? Am. Meteorol. Soc. 19, 4631–4637.

Lee, T.N., Yoder, J., Atkinson, L., 1991. Gulf stream frontal eddy influence on productivity of the southeast U.S. continental shelf. J. Geophys. Res. 96, 22191–22205.

Liu, Y., Weisberg, R.H., Hu, C., Kovach, C., Riethmüller, R., 2011a. Evolution of the loop current system during the deepwater horizon oil spill event as observed with drifters and satellites. In: Liu, Y., et al. (Eds.), in monitoring and modeling the Deepwater Horizon Oil Spill: a record-breaking enterprise. Geophysical Monograph Series, 195. AGU, Washington, DC, pp. 91–101, http://dx.doi.org/10.1029/2011GM001127 (in press).

Liu, Y., Weisberg, R.H., Hu, C., Zheng, L., 2011b. Tracking the deepwater horizon oil spill: a modeling perspective. Eos Trans. 92 (6), 45–46.

Mahon, R., Oxenford, H., 1999. Precautionary assessment and management of dolphinfish in the Caribbean. Sci. Mar. 63, 429–438.

Olson, D.B., Brown, O.B., Emerson, S.R., 1983. Gulf stream frontal statistics from Florida Straits to Cape Hatteras derived from satellite and historical data. J. Geophys. Res. 88, 4569–4577.

Oxenford, H., Hunte, W., 1986. Preliminary investigation of the stock structure of the dolphin, *Corphaena hippurus*, in the western central Atlantic. Fish. Bull. 84, 451–460.

Oxenford, H., 1999. Biology of dolphinfish (*Coryphaena hippurus*) in the western central Atlantic: a review. Sci. Mar. 63, 277–301.

Rivera, G., Appeldoorn, R., 2000. Age and growth of dolphinfish *Coryphaena hippurus*, off Puerto Rico. Fish. Bull. 98, 345–352.

Rodríguez-Ferrer, G., Rodríquez-Ferrer, Y., Matos-Caraballo, D., Lilyestrom, C., 2004. Comparison of dolphinfish (*Coryphaena hippurus*) commercial and recreational fisheries in Puerto Rico during 2000–2003. Gulf Carib. Fish. Inst. 57, 297–316.

Schmeits, M.J., Dijkstra, H.A., 2001. Bimodal behavior of the Kuroshio and the Gulf Stream. J. Phys. Oceanogr. 31, 3435–3456.

Soloviev, A., Wood, J., 2011. Southward flow under the Florida Current and Coastal Countercurrent in the Straits of Florida. In: IAPSO Session PO-6 29 June, http://www.dep.state.fl.us/coastal/programs/coral/documents/2011/LBSP/11-03/Soloviev_and_Wood_TAC_Nov2011.pdf

Taquet, M., Dagorn, L., Gaertner, J.-C., Girard, C., Aumerruddy, R., Sancho, G., Itano, D., 2007. Behavior of dolphinfish (*Coryphanea hippurus*) around drifting FADs as observed from automated acoustic receivers. Aquat. Living Resour. 20, 323–330.