Fisheries Research 209 (2019) 186–195

Contents lists available at ScienceDirect

Fisheries Research

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

Acoustic telemetry array evolution: From species- and project-specific designs to large-scale, multispecies, cooperative networks

Robert D. Ellis[a,*], Kerry E. Flaherty-Walia[a], Angela B. Collins[b], Joel W. Bickford[a], Ross Boucek[c], Sarah L. Walters Burnsed[a], Susan K. Lowerre-Barbieri[a,d]

[a] *Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, 100 8th Avenue Southeast, St. Petersburg, FL, 33701, USA*
[b] *University of Florida IFAS Extension, Florida Sea Grant, 1303 17th Street West, Palmetto, FL, 34221, USA*
[c] *Bonefish & Tarpon Trust, 135 San Lorenzo Avenue, Suite 860, Coral Gables, FL, 33146, USA*
[d] *Fisheries and Aquatic Science Program, School of Forest Resources and Conservation, University of Florida, 7922 Northwest 71st Street, Gainesville, FL, 32653-3071, USA*

ARTICLE INFO

Handled by George A. Rose

Keywords:
Acoustic telemetry
Movement
Artificial reef
Gulf of Mexico
Grouper
Red drum

ABSTRACT

Acoustic telemetry is a powerful tool for investigating the movement ecology of aquatic animals. As the number of studies using passive acoustic telemetry technology has grown in recent years, so has membership in regional collaborative networks in which methodologies and detection data are shared among researchers. These networks can significantly augment research projects by increasing the geographic coverage of detection data beyond the initial monitored area, and encourage the development of research collaborations with the goal of improving aquatic research management. As tags expire and projects end, researchers must decide whether to maintain their receiver stations, adjust the configuration to accommodate a new scope of research, or remove the stations. We assessed telemetry data from two projects designed to monitor fishes in nearshore and offshore habitats of the eastern Gulf of Mexico to determine the configuration of receiver stations most informative for network scale monitoring. Modeled on the Index of Relative Importance commonly used to analyze fish diets, the Receiver Efficiency Index (REI) allowed us to reduce the size of the two arrays from 59 to 24 and 33 to 21 stations, reductions of 59% and 27%, while retaining more than 75% of all detections. The application of this method has general relevance to understanding the spatial dynamics of these arrays while providing researchers with a quantitative tool to guide decision making that can maximize spatial coverage at the lowest maintenance cost.

1. Introduction

Through technological improvements, the capacity to track aquatic animals using passive acoustic telemetry has improved tremendously over the past 20 years. Passive acoustic telemetry—the use of acoustic monitors capable of recording the presence of animals tagged with acoustic transmitters (Heupel et al., 2006)—allows researchers to track aquatic animals at unprecedented spatial and temporal resolutions. By providing nearly continuous data for tagged animals within the detection range of receivers, passive tracking is useful for determining site fidelity and spatial and temporal behaviors that are difficult to assess with commonly used external tagging methods (Pecl et al., 2006; Lowerre-Barbieri et al., 2013; Ajemian et al., 2018). As acoustic monitoring technology has advanced, so has the affordability of equipment, allowing it to become commonplace in many research disciplines, including fisheries science, ecology, and conservation (Hussey et al., 2015).

With the growing use of this technology, the spatial coverage of passive acoustic telemetry has expanded from a few distinct and geographically isolated areas to regional networks of arrays (Hussey et al., 2015). The monitoring capabilities afforded by widespread use of common technology presents opportunities for new research facilitated through collaborations among researchers that share data beyond the scope of individual initiatives. Researchers can now maximize data collection by expanding passive acoustic arrays and combining efforts to better understand the spatiotemporal patterns of animal movements (Ellis et al., 2014; Guttridge et al., 2017; Pratt et al., 2018; Crossin et al., 2017). As aquatic telemetry networks evolve there is a need to

* Corresponding author.
E-mail addresses: robert.ellis@myfwc.com (R.D. Ellis), kerry.flaherty-walia@myfwc.com (K.E. Flaherty-Walia), abcollins@ufl.edu (A.B. Collins), joel.bickford@myfwc.com (J.W. Bickford), ross@bonefishtarpontrust.org (R. Boucek), sarah.burnsed@myfwc.com (S.L. Walters Burnsed), susan.lowerre-barbieri@myfwc.com (S.K. Lowerre-Barbieri).

https://doi.org/10.1016/j.fishres.2018.09.015
Received 30 April 2018; Received in revised form 14 September 2018; Accepted 15 September 2018
Available online 04 October 2018
0165-7836/

address broader issues in terms of spatial coverage including the maintenance of deployed receivers for consistent monitoring, identifying gaps in coverage, and deploying new receivers in key habitats to build monitoring capacity at the regional or Large Marine Ecosystem scale (Lowerre-Barbieri et al., 2017). Furthermore, the shift to collaborative, connected units of passive acoustic arrays and an increased emphasis on leveraging resources will impact future decisions regarding array design and tag deployment. Rather than designing arrays to maximize detections of one or more species of interest, researchers working in conjunction with partners from network organizations may be motivated to consider modified array designs that will also facilitate data collection for their colleagues. Maintaining acoustic telemetry arrays is expensive and time-consuming, and methods that enable researchers to evaluate the cost and benefits of reducing or modifying arrays are needed.

An ongoing challenge for acoustic telemetry networks is to maintain a balance between continuity in spatial coverage while allowing arrays to evolve with changing research objectives. The Integrated Tracking of Aquatic Animals in the Gulf of Mexico (iTAG) network was developed in 2014 so that researchers could share detections across telemetry arrays deployed from Texas to Florida (http://myfwc.com/research/saltwater/telemetry/itag). As of May 2017, iTAG had 85 members from three countries with > 1000 tags and > 2000 receivers deployed across more than 35 arrays deployed throughout the Gulf (Lowerre-Barbieri et al., 2017). The iTAG Data Exchange, an automated, web-based platform designed for the exchange of data between detection collectors and tag owners, provides the ability for data to be shared among researchers within the iTAG network (e.g., Pratt et al., 2018), as well as members of array networks on the east coast of the US, demonstrating the geographic scope and value of this tool.

The growth of passive acoustic telemetry technology and of networks of associated researchers demands novel methodologies to inform decision-making regarding receiver station retention through time and beyond the scope of individual project objectives. In this study, we used data collected by two independent arrays in the iTAG network. Located on the central Gulf coast of Florida and developed by researchers at the Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute (FWC/FWRI), these arrays were deployed to monitor red drum (*Sciaenops ocellatus*) in nearshore coastal waters and Atlantic goliath grouper (*Epinephelus itajara*) and gag (*Mycteroperca microlepis*) on natural and artificial reef habitats of the west Florida shelf. We conducted a cross-site comparative study as a proof of concept of a method that provides a quantitative approach to optimizing array configuration based on the detection value of each receiver. The metric we propose is modified from an index commonly used in fish-diet studies, the Index of Relative Importance (IRI; Pinkas et al., 1971; Hart et al., 2002), which we used to provide a weighted and relativized value of the importance of each station in an acoustic array. We applied this method to data collected from two discrete acoustic arrays to demonstrate how this analysis can be applied and interpreted to guide future decisions on array maintenance that will maximize network utility while minimizing effort.

2. Materials and methods

2.1. Acoustic telemetry networks

The two arrays analyzed for this study were located in the eastern Gulf of Mexico and are part of the iTAG network (Fig. 1). The iTAG network seeks to increase and facilitate the capability of researchers in the Gulf to assess movement and spatial ecology of aquatic animals through improved networking, increased infrastructure, and sharing of acoustic transmitter detection data. Data are shared by iTAG members through a web-based platform, the iTAG data exchange, in which members can upload detections from their arrays of non-study species and be notified via email when those tags are claimed by other network members (http://myfwc.com/research/saltwater/telemetry/itag/orphan-tag-database/). Members can also upload a list of their deployed tag numbers and be automatically notified when other members upload detections of those tags. The FACT Network provides a similar service for acoustic telemetry researchers on the Florida Atlantic coast. FACT network members deploy and maintain receivers along a continuum of coastal habitats from freshwater estuaries to marine waters of the adjacent continental shelf from Georgia to the Florida Keys, as well as the Bahamas, Puerto Rico, and the U.S. Virgin Islands. Members of FACT have access to a shared database of array stations and tag metadata and are expected to directly share detection data with other FACT Network members. Many researchers, including the authors, belong to both iTAG and FACT, and the networks work closely to share tag IDs and other information.

2.2. Passive acoustic telemetry arrays

We analyzed data collected from two project-specific arrays located in the Gulf of Mexico off west central Florida: a nearshore array (the coastal array), deployed to monitor red drum, and an offshore array (the reef array), deployed to monitor goliath grouper and gag (Fig. 1). These two arrays are typical, based on size and duration of deployment, of other arrays within the iTAG and FACT networks, but differed in terms of the design configuration, study goals, and life history characteristics of focal species.

2.2.1. Coastal array

The coastal array was initially deployed in 2012 at nearshore sites off Tampa Bay and Charlotte Harbor (plus two sites within the estuary) to track movements of red drum (Lowerre-Barbieri et al., 2016a, 2016b). The Tampa Bay section of the array comprised 33 stations, 20 at sites at which red drum aggregations had been identified and 13 to fill in spatial gaps, primarily in the southern portion of this sampling area (Fig. 1). For the Charlotte Harbor section of the array 15 receivers were initially deployed in an evenly spaced grid directly offshore of the estuary, with four additional stations added in 2012 and 2013, two at red drum aggregation sites and two located within the estuary to monitor subadults which had been captured and released there. In August 2014, seven more stations were added to the Charlotte Harbor section and in the area between Tampa Bay and Charlotte Harbor, again in locations where red drum aggregations had been observed. Receivers (VR2W; Vemco, Bedford, Nova Scotia, Canada) were moored using sand augers (122 cm long) screwed into the sediment to an approximate depth of 0.5 m. The receiver was attached to the sand auger with heavy-duty cable ties and positioned on the auger so that the hydrophone was approximately 0.8 m above the substrate and elevated above the metal auger. A range test was performed prior to deployment, from September 2010 to January 2011, in the Tampa Bay section of the array, with a detection rate of more than 50% observed at a range of 400 m. Routine array maintenance included replacing receivers at stations approximately once per quarter. During the study period (2014–2015), six sites in the coastal array experienced receiver failure or were lost (operational for 518–716 days).

2.2.2. Reef array

The reef array was deployed initially in 2011 to monitor the effects of catch and release angling on goliath grouper. Sites were originally identified based upon goliath grouper preference for artificial reefs (Collins et al., 2015) and the array was enlarged in 2014 to incorporate natural reef and hard-bottom habitats after gag were added to research initiatives. Sites were chosen to represent a range of reef sizes and spanned the general range of depths at which most recreational angling for these species occurs on the West Florida Shelf (10–40 m, Fig. 1). Sites were also chosen based on relative proximity to one another to maximize the odds of detecting fish moving between sites. Range detection tests were performed at six sites chosen as representative of the

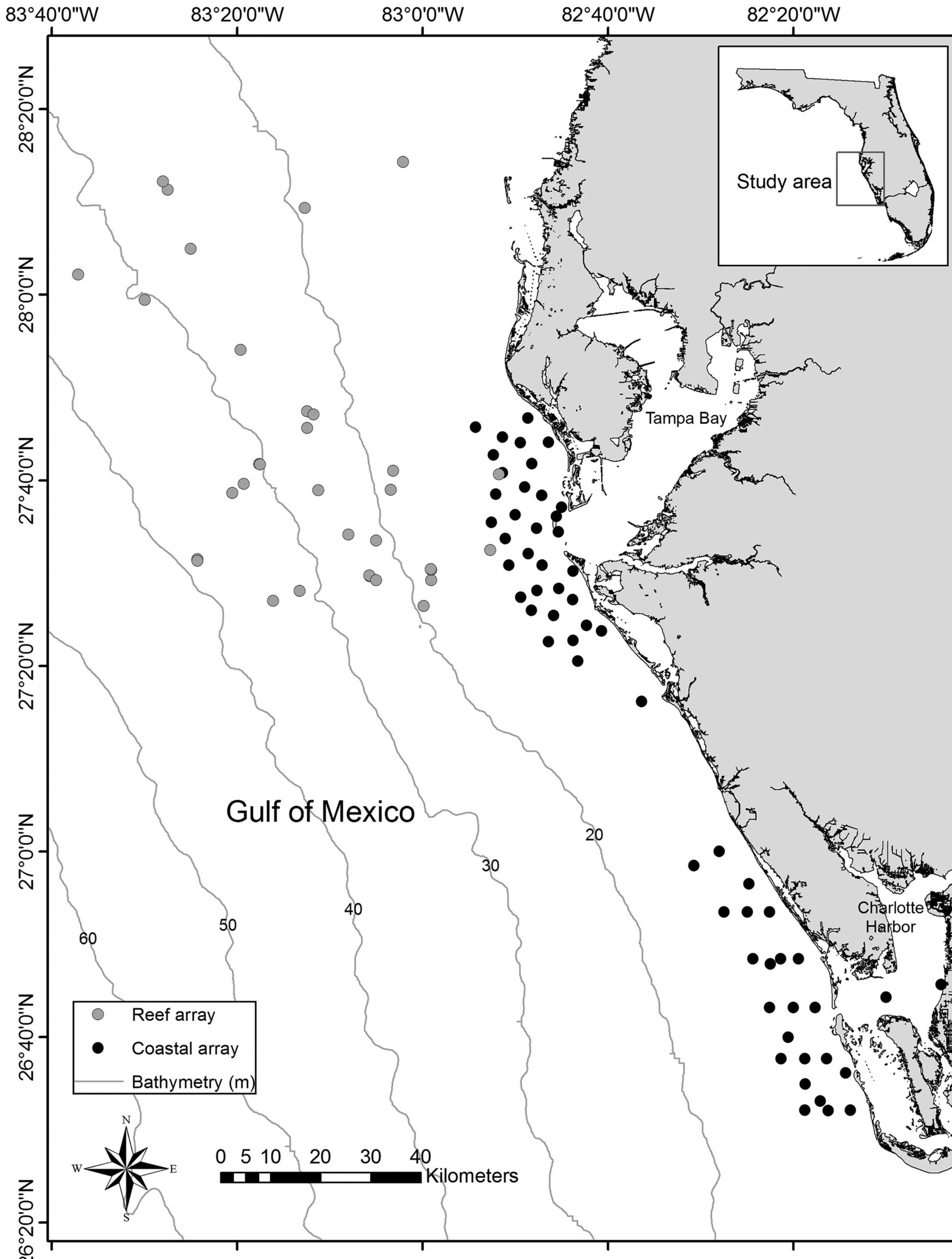

Fig. 1. General locations of receivers deployed, 2014–2015 in the reef (gray) and coastal (black) arrays. Bathymetry isobaths are located every 10 m, starting with the 20 m isobath closest to shore.

habitat characteristics and depths comprised by the array (Collins, 2014). These tests were completed before tagging fish to ensure that acoustic receivers were placed for optimal (> 90%) detection of acoustic tags (Collins, 2014). To maximize detection capability, one to four receivers (depending upon reef habitat features) were positioned 50–100 m from the center of each site. This distance was conservative, since the receivers have a listening radius of 150–750 m, depending on environmental conditions (Pincock, 2008). Before deployment, receivers were coated with a copper-based antifouling paint to prevent biofouling and the resulting reduction in detection capability (Heupel et al., 2006). Receivers were deployed at 33 stations during at least some of the study period from 1 January 2014 through 31 December 2015; 14 stations were added to the reef array during the study period (operational for 415–696 days). All receivers were maintained and downloaded quarterly as described above.

2.3. Analytical methods

2.3.1. Detection data

We used the iTAG Orphan Tag Database and the FACT Network tag metadata list to identify unknown tags detected within the two focal arrays. Tag owner data were merged by tag number and transmitter code-space with acoustic detection data from the coastal and reef arrays from January 2014 through December 2015. Detections from unknown tags for which we could not determine the tag owner or species were excluded. The validity of the remaining detections was determined with automated filtering of the detection data in SAS (SAS v.9.3, enterprise guide 5.1, SAS Institute Inc. 2017) based on the array configurations and expected movements of target species. We removed detections if a given tag was detected fewer than five times per day or if the time between detections at multiple receivers was less than 10 min. In some cases, detections were retained if these receivers were deployed close together and an individual could realistically swim between them in 10 min (i.e., some receivers were deployed on the same reef in the reef array).

To standardize detection information among species with different daily behavioral patterns (e.g., small-scale vs. large-scale movements, transient versus resident), we calculated detection days for each tagged fish per receiver. Detection days were defined as a valid detection for each day at each individual receiver station, therefore, a fish that moved between stations in the same day could have multiple detection days within a given 24-hour period, while fish that were detected at only a single station would only have a single detection day for that same 24-hour period. Summary statistics were calculated for each array, and numbers of total detections, detection days, species, and tags detected at each receiver were tested for differences between arrays with non-parametric Wilcoxon-Mann-Whitney rank tests (significance at $p < 0.05$ was based on the normal approximation of the Z test statistic; SAS Institute Inc., 2017). Owners of tags of nontarget species provided explicit permission for us to report that their species were detected within our arrays (see Acknowledgements).

2.3.2. Index development

To determine the relative importance of monitored sites within each array, we developed the Receiver Efficiency Index (REI) based on the IRI method commonly used in diet studies of fishes and other animals (Cortés, 1997; Hart et al., 2002). The general form of the IRI is

$$IRI = (N + V)\,F$$

where N = a numerical percentage, V = a volumetric percentage, and F = a frequency-of-occurrence percentage (Pinkas et al., 1971). We applied this index to acoustic tag detection data rather than diet data by recognizing the inherent similarities between these data types. Essentially, the IRI takes two forms of information, the number and volume of items counted in stomach contents, and scales these by the frequency in which they occur. Acoustic telemetry detection data can similarly be separated into numerical (tags or species), volumetric (detections), and frequency (detection days) information. Based on these similarities, we developed the REI for each receiver (r) within a given array (a) based on the following equation:

$$REI_r = \frac{T_r}{T_a} * \frac{S_r}{S_a} * \frac{DD_r}{DD_a} * \frac{D_a}{D_r}$$

where T = number of tags, S = number of species, DD = detection days, and D = number of days the array was deployed (D_a) or an individual receiver was in the water and operational (D_r). REI values were calculated for each receiver by multiplying the proportion of tags by the proportion of species and the proportion of detection days for each receiver relative to the entire array. The three-way product of these proportions was then scaled by the proportion of time that each receiver was operationally deployed to account for periods when no detection data were collected. Percent REI values were calculated for each receiver site by dividing each REI value by the sum of all REI values for each array.

For each array, REI values were calculated for detections of incidental (nontarget) species, target species, and all species combined so that we might investigate spatial patterns of receiver importance. Percent REI values were plotted in a geographical information system (GIS) to facilitate these comparisons. To evaluate array performance during the study period (2014–2015), we used the REI values to determine the minimum size of each array necessary to meet three performance benchmarks of the full array, modified from those developed by Steckenreuter et al. (2017): 1) 75% of all tags detected; 2) 100% of all species detected; and 3) 75% of total detections. We added a fourth benchmark value: 4) 100% of tag of nontarget species, because we wanted to ensure that minimized arrays retained detections of all nontarget species to maximize their value for network collaborators. To calculate the number of stations in each minimized array, we first examined the REI values for natural breakpoints to be used as threshold cutoffs for selecting receiver stations, then each reduced array was tested to see if it met all benchmarks. If all benchmarks were not met, receiver stations were added by order of importance until all benchmarks were met. This method, which ordered stations by relative importance first, was chosen over an algorithmic method which would return the absolute minimum set of stations that would meet all benchmarks but may sacrifice some individually important stations.

3. Results

For the January 2014–December 2015 study period, the coastal and reef arrays provided detection data from 59 and 33 stations, respectively (Table 1). Each array was most efficient at detecting tags from its respective target species but also detected nontarget species tagged elsewhere by other researchers (Tables 2 and 3). Due to the life history (i.e., high site fidelity) of the target species tagged in the reef array, the total number of both detections (Wilcoxon-Mann-Whitney rank tests: $Z = 5.01$, $p < 0.01$) and detection days ($Z = 3.20$, $p = 0.01$) were more numerous in this array compared to the coastal array. However, the mean number of species detected per station, was similar between arrays ($Z = 1.49$, $p = 0.14$), while the mean number of unique tags detected per station was higher in the coastal array than in the reef array ($Z = -4.35$, $p < 0.01$). Overall, 11 species (10 of them nontarget) were detected in the coastal array and 7 species (5 nontarget) were detected in the reef array. All species detected in the reef array

Table 1
Summary statistics (number, mean, standard deviation, and maximum number) for tags, detections, detection days, and species by station for the coastal and reef arrays, 2014–2015.

Variable	N	Mean	SD	Max
Coastal stations	59			
Tags	148	28.20	18.06	78
Detections	105,340	1,785.42	4,548.31	34,408
Detection days	4,950	83.90	82.50	455
Species	11	2.71	1.02	5
Wreck stations	33			
Tags	164	13.58	9.09	47
Detections	2,224,819	67,418.76	117,708.84	530,015
Detection days	9,187	278.36	280.06	1,050
Species	7	3.09	1.16	5

Table 2
Detections by species from the coastal array: number of tags detected per species; total number of detections per species; total detection days (DDs) per species; number of detections (detect.) per species as a % of all detections within array. Target species is in bold text.

Scientific name	Common name	No. tags	No. DDs	No. detect.	% detect.
Sciaenops ocellatus	**Red drum**	120	4,630	101,428	96.286%
Epinephelus itajara	Goliath grouper	1	60	1,106	1.050%
Carcharhinus leucas	Bull shark	11	141	1,029	0.977%
Ginglymostoma cirratum	Nurse shark	2	23	570	0.541%
Carcharhinus limbatus	Blacktip shark	4	24	521	0.495%
Carcharhinus brevipinna	Spinner shark	1	26	333	0.316%
Megalops atlanticus	Atlantic tarpon	4	33	296	0.281%
Galeocerdo cuvier	Tiger shark	2	9	35	0.033%
Acipenser oxyrinchus desotoi	Gulf sturgeon	1	1	12	0.011%
Mycteroperca microlepis	Gag	1	2	5	0.005%
Pristis pectinata	Smalltooth sawfish	1	1	5	0.005%
Totals		**148**	**4,950**	**105,340**	**100.000%**

were also detected in the coastal array, except for a great hammerhead shark (*Sphyrna mokarran*), which was detected in the reef array but never within the coastal array. Across both arrays, most of the non-target species detected were elasmobranchs (six species; Tables 2 and 3). Despite our efforts, we were unable to match some tags with their owners: 11 tags (1765 total detections) in the coastal array and 2 tags (57 detections) in the reef array.

The results of the REI analysis showed that, within an array, the relative importance of stations was uneven, and a smaller subset of stations could be used to retain enough detections to fulfill benchmarks: 24 of 59 stations (40.7%) in the coastal array, and 21 of 33 (63.6%) stations in the reef array (Fig. 2). We evaluated the REI results compared to these benchmarks at two breakpoints that seemed to naturally delineate the stations: %REI > 2 and %REI > 1. In the coastal array, keeping only the 15 stations (25.4%) with a %REI > 2 retained 96.6% of all tags detected within the array (benchmark #1), 100% of all species (benchmark #2), but only 68.4% of detections (benchmark #3). Keeping all stations with a %REI value > 1 (23 of 59 stations, 40.7%) retained 76.9% of all detections to satisfy benchmark #3. By keeping all stations with a %REI > 1 plus one additional station (#282), all four benchmarks could be met. Station #282 was a relatively low-ranked station but was the only station at which a tag of a nontarget bull shark was detected (see Appendix for a description of full station ranks). For the reef array, 16 stations (48.5%) had a %REI value > 2, while 20 stations (60.6%) had %REI values > 1. Keeping only the stations with %REI values > 2 retained 82.9% of all tags detected (benchmark #1) and 85.2% of all detections (benchmark #3). To meet benchmark #2 (100% of all species detected), it was necessary to keep all 20 stations with %REI values > 1 plus one additional station (station #30, rank = 25), and to meet benchmark #4 (100% of nontarget tags) it was necessary to keep all 20 stations with a %REI values > 1 plus four additional stations (24 total stations; 72.7% of the full array).

Spatial patterns of receivers with high REI values differed between the two arrays and were driven by the relative number of target versus nontarget detections. In the coastal array the highest REI values were found along the western edge of the Tampa Bay section and in the northern part of the Charlotte Harbor section (Fig. 3). Stations in the reef array with high REI values were more diffuse and seemed to be driven more by the species detected (Fig. 4). Both gag and goliath grouper were detected most often at the site where they were tagged; for gag this resulted in more detections in the northern part of the array, while goliath grouper were most often detected in the southern part of the array. Nontarget species were most often detected in the southern part of the reef array. In the coastal array, all 59 stations detected red drum tags and all but four stations detected tags from nontarget species (Fig. 3; Appendix 1). The target species tagged within the reef array, gag and goliath grouper, were detected at 18 and 10 (of 33 total) reef array stations, respectively. All stations in the reef array detected at least one tag of a nontarget species, while six stations detected only tags from nontarget species (Fig. 4 Appendix 2). The coastal array was separated into two sections, receivers located west of Tampa Bay or west of Charlotte Harbor, to explore spatial differences in detections across the two arrays; the reef array receivers were not separated. Because the coastal and reef arrays were close to each other, almost half of the tags (47.4%) were detected at more than one of the three spatial locations (Table 4). No tagged fish were detected in both the reef array and the Charlotte Harbor section of the coastal array, but 40 fish were detected in all three locations: the reef array and in both sections of the coastal array. Only a single gag and one goliath grouper were detected moving between arrays. However, most of the tagged red drum (59.2%) were detected in both the coastal and reef arrays. The proportion of target and nontarget species detected moving between arrays was approximately the same: 73 of 198 (36.9%) target tags and 10 of 32 (31.3%) nontarget tags were detected in both arrays (Table 4).

4. Discussion

The growing prevalence of large-scale regional networks of passive acoustic telemetry arrays has increased the need for reliable methods for evaluating the efficacy of receiver arrays and guiding decision-making that will maintain network connectivity after specific studies conclude. Here we have demonstrated such a method based on a

Table 3
Detections by species from the reef array: number of tags detected per species; total number of detections per species; total detection days (DDs) per species; number of detections (detect.) per species as a % of all detections within array. Target species are in bold text.

Scientific name	Common name	No. tags	No. DDs	No. detect.	% detect.
Mycteroperca microlepis	**Gag**	**71**	**7,509**	**2,001,057**	**89.942%**
Epinephelus itajara	**Goliath grouper**	**7**	**979**	**213,226**	**9.584%**
Sciaenops ocellatus	Red drum	71	589	5,184	0.233%
Ginglymostoma cirratum	Nurse shark	2	46	3,800	0.171%
Carcharhinus leucas	Bull shark	9	48	1,497	0.067%
Galeocerdo cuvier	Tiger shark	3	14	48	0.002%
Sphyrna mokarran	Great hammerhead shark	1	1	7	0.000%
Total		**164**	**9,186**	**2,224,819**	**100.000%**

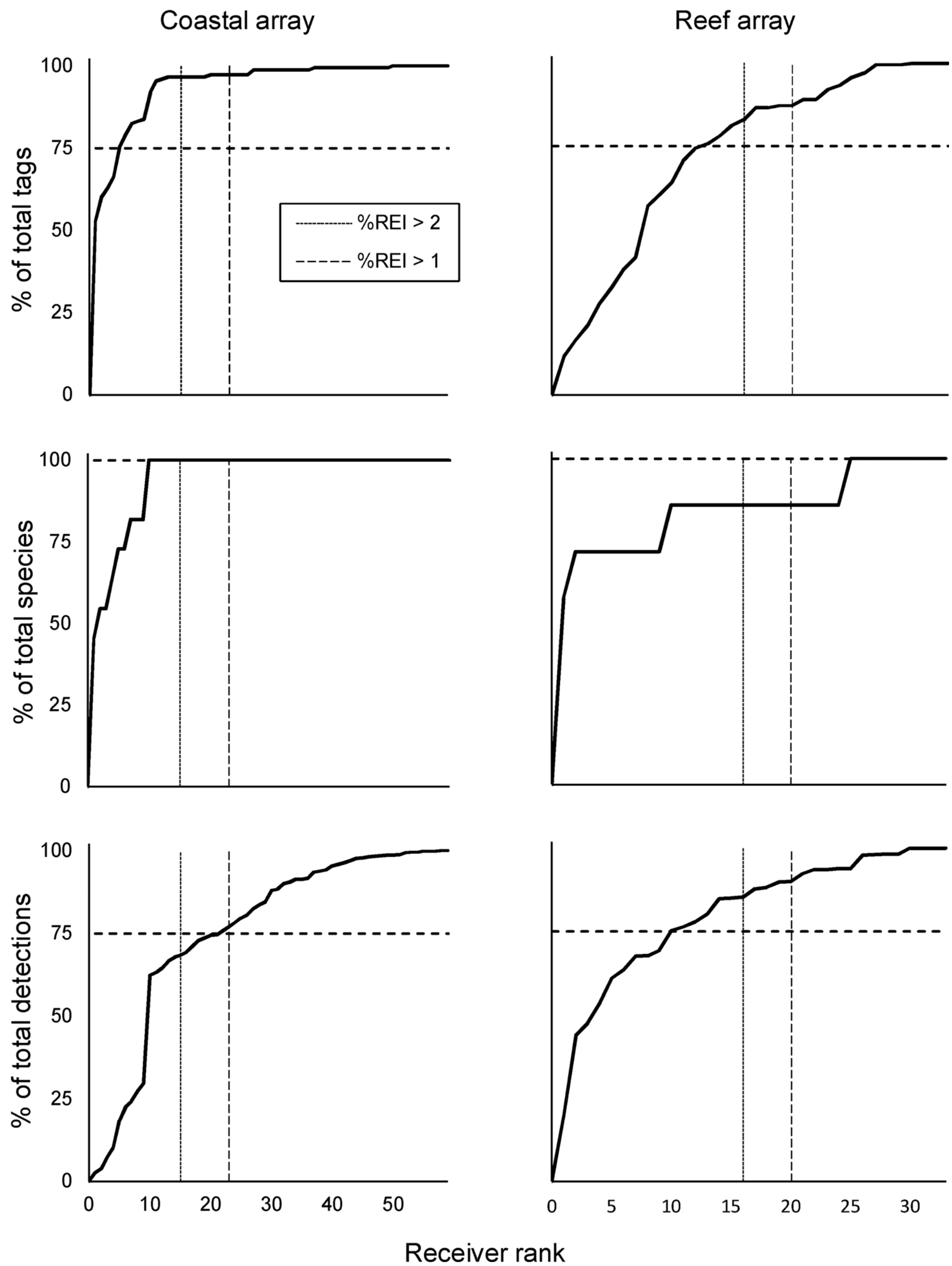

Fig. 2. Cumulative curves describing the effect of adding receivers by ranked %REI value relative to benchmarks (horizontal dashed lines) for retained tags (top), species (middle), and total detections (bottom) in the coastal (left) and reef (right) arrays. %REI > 2 and > 1 are shown by the dotted and dashed vertical lines.

commonly used relativizing index by comparing the performance of two different arrays. Our analysis found that similar data could be collected with a reduction in the number of receivers deployed. The REI analysis represents a useful tool for the quantitative evaluation of each receiver location after the completion of specific research projects. By assigning an efficiency value to each station, researchers can identify and eliminate redundant or low-value stations, conserving significant time and expense and maximizing the capability to maintain an array with the minimum number of receivers for acceptable efficiency beyond the scope of discrete research projects.

One of our objectives in developing the REI analysis was to develop a tool for quantitatively assessing the performance of individual stations in order to identify the minimum number of receivers we could maintain to continue providing data to regional monitoring efforts. To develop deployment strategies that best align with study objectives, researchers must rely on their knowledge of species behaviors and spatial distributions when designing telemetry arrays (Heupel et al., 2006). By the end of a study, some stations often turn out to be unnecessary or redundant. Many telemetry studies occur over relatively long time frames and thus the REI analysis can provide a quantitative framework for assessing and identifying low-performing receiver stations that could be deployed elsewhere in future arrays. This aspect of the REI approach should be most valuable to researchers operating with a finite number of receivers or with a limited budget, as it will allow for efficient array maintenance with minimal data sacrifice.

We analyzed the two arrays after the projects were complete, but this analysis could be informative if performed at multiple points during a study. If combined with range testing performed during preliminary work, an REI analysis could help build a stronger, more comprehensive array design at the outset of a study. Alternatively, conducting this analysis mid-study may help researchers understand how their array is performing, but using the results of an REI analysis to

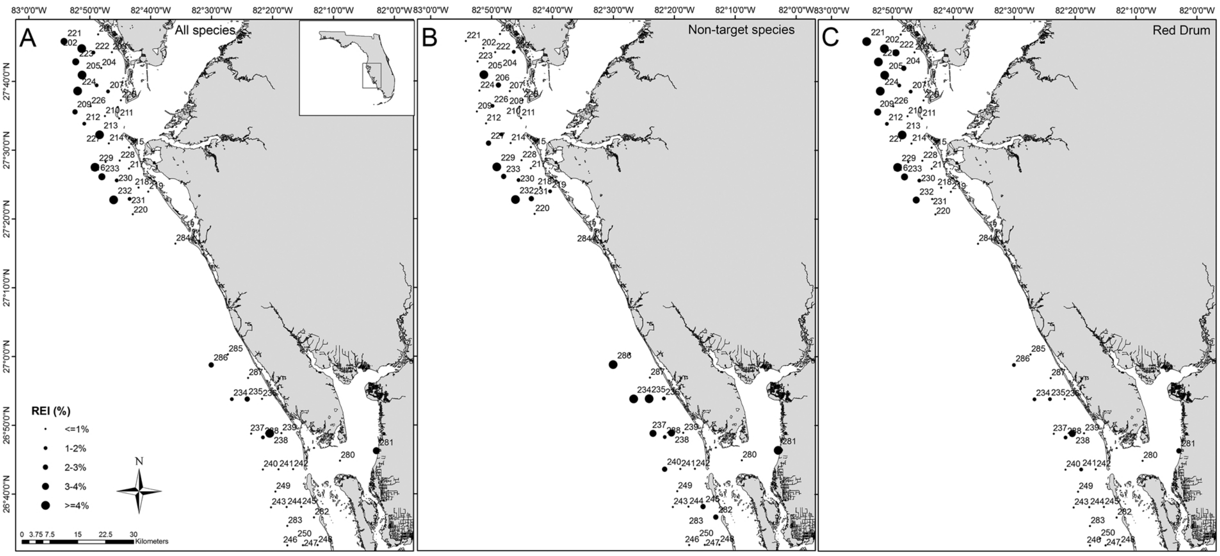

Fig. 3. %REI results for all species detected (A), all nontarget species detected (B), and all red drum detected (C) within the coastal array, 2014–2015.

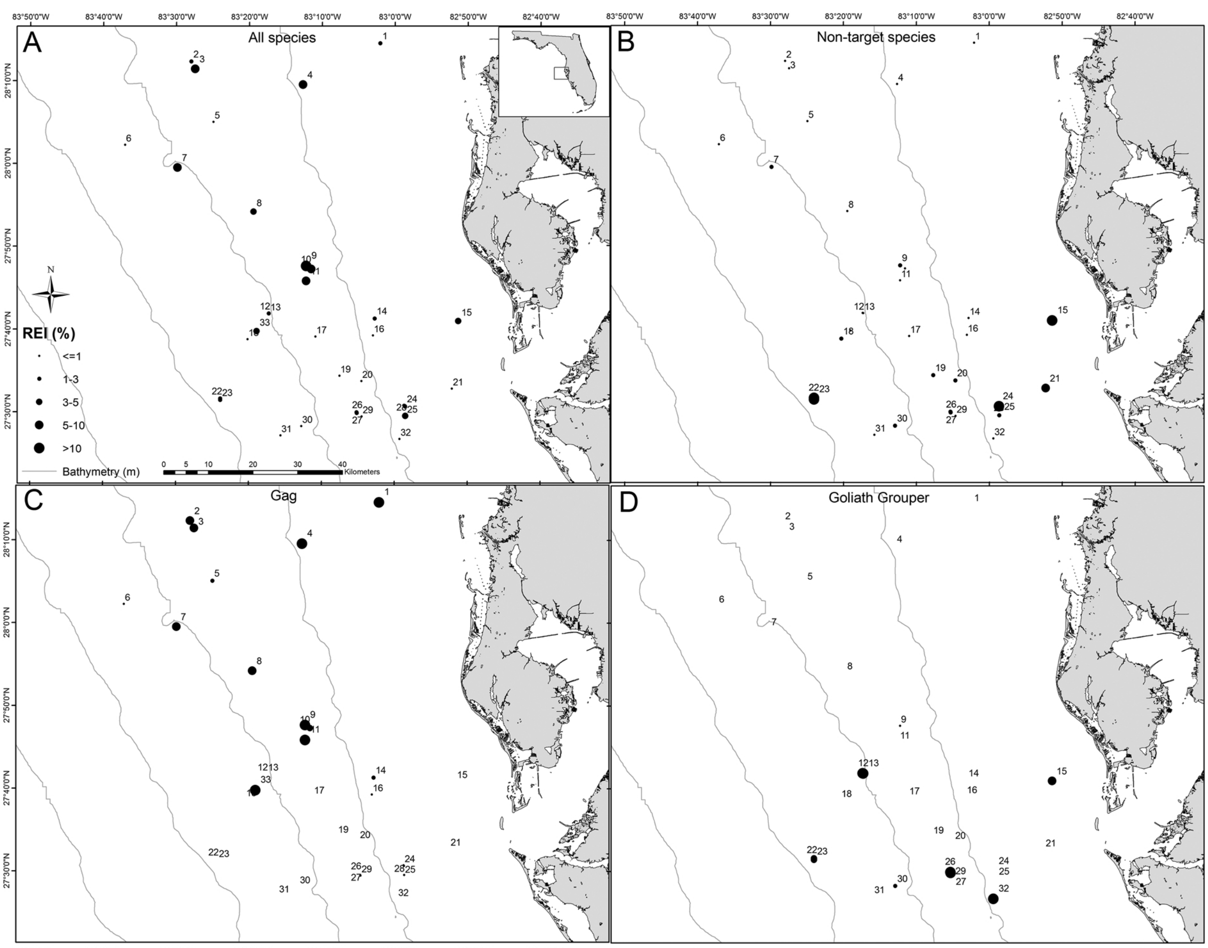

Fig. 4. %REI results for all species detected (A), all nontarget species detected (B), all gag detected (C), and all goliath grouper detected (D) within the reef array, 2014–2015.

relocate stations mid-study complicates study design and may reduce the researchers' ability to assess spatial or temporal variations in movement patterns or to detect opportunistic or environmentally forced movements caused by stochastic events (e.g., hurricanes, cold kills, harmful algal blooms, etc.; Walters et al., 2013; Boucek et al., 2017a). When conducted as a post hoc analysis, the REI approach can help determine whether sites identified as important at the start of the study were in fact important or other stations turned out to be more important. For example, coastal array station #286, located in the extreme northwest corner of the Charlotte Harbor section, was the most

Table 4
Number of individuals (tags), by species, detected within multiple array locations, 2014–2015. TB = coastal array receiver stations west of Tampa Bay. CH = coastal array receiver stations west of Charlotte Harbor. Reef = reef array receiver stations. Total detected indicates the number of tags detected during the study period across all locations; the %Total is the percentage of tags that were detected in multiple array locations. Target species are indicated by bold text.

Common Name	Locations detected			Total detected	% Total
	TB, CH, Reef	TB, CH	TB, Reef		
Atlantic tarpon		1		4	25.0%
Blacktip shark				4	0.0%
Bull shark	6	1		14	50.0%
Gag			1	71	1.4%
Goliath grouper	1			7	14.3%
Great hammerhead shark				1	0.0%
Gulf sturgeon				1	0.0%
Nurse shark	1	1		3	66.7%
Red drum	31	21	40	120	76.7%
Smalltooth sawfish				1	0.0%
Spinner shark		1		1	100.0%
Tiger shark	1		1	3	66.7%
Total	40	25	42	226	47.4%

important station in the entire coastal array in terms of nontarget detections (%REI = 10.76) but was ranked 20th for red drum detections (%REI = 1.80; see Appendix). Thus, in the context of the red drum study this was a minimally important station, but in the broader network context it was an important station and without the REI analysis we may have underestimated the importance of this station for our network partners.

While the REI method uses the currency of station efficiency to evaluate array performance, it is critical to consider what this means in the context of individual studies. In some cases, not detecting tagged animals can be informative regarding habitat suitability. Furthermore, zero or low numbers of detections do not necessarily mean that a station is redundant. For example, within the reef array there were six stations that never detected either of the target species during the period evaluated in this study even though visual surveys conducted before the project started confirmed that both goliath grouper and gag were present at each site. The reef array was initially deployed in 2011 to monitor goliath grouper behaviors and survival after catch and release and then expanded in 2013 to assess gag behaviors (Collins, 2014; Collins and Barbieri, 2017). Most of the goliath grouper tags had expired by 2014, but when the reef array was expanded to include gag sites, all the original reef receiver stations were retained to maximize potential detections of gag tagged in the area. However, tagged gag were rarely detected moving between sites and all but one of the six reef array sites that did not detect either goliath grouper or gag were sites selected for goliath grouper, not part of the gag expansion. As these projects evolved, monitoring goals shifted from defining short-term survival and post-release behavior of individuals to characterizing long-term site fidelity. This example highlights the various trade-offs that researchers must consider. Here the REI analysis proved a useful tool for determining the performance of individual receiver locations across multiple objectives.

Despite the importance of evaluating array performance, there are surprisingly few tools available with which researchers can conduct post hoc evaluations of their arrays. Most of the available literature focuses instead on array design (Heupel et al., 2006; Kraus et al., 2018) or assessing tag detectability and receiver performance (Clements et al., 2005; How and de Lestang, 2012; Welsh et al., 2012; Farmer et al., 2013; Kessel et al., 2014). There are also abundant examples of methods for describing and elucidating patterns of movement of individual species within arrays, especially for analyzing fine-scale movements (Simpfendorfer et al., 2002; Andrews et al., 2011; Baktoft et al., 2017), or for applying social network analysis to detection data (Jacoby et al., 2012; Finn et al., 2014; Boucek et al., 2017b). The interpreted performance of any acoustic telemetry array will depend largely on the research questions that inform array design, as well as the number and type of species at large within an array in any given time frame. Thus, any array-optimization procedure must consider the specific properties of the array in question and must be conducted case by case. We know of only one other example of a post hoc analysis performed at the array level, by Steckenreuter et al. (2017), who described a process for streamlining acoustic telemetry curtains (linear arrays or gates extending across migration corridors). Their goal was similarly to minimize effort while maintaining detectability, but their method dropped stations sequentially until the remaining stations did not meet benchmarks. This method may be better suited for linear (i.e., curtains or gates) or grid arrays where detections change in predictable patterns (e.g., decline with increasing distance from shore). However, we did not find this method effective for analyzing either of our arrays, which were set up in a "fisheries" format (*sensu* Heupel et al., 2006).

Rather than present the results of an array-specific optimization method, one of our goals in constructing the REI approach was to develop a customizable optimization tool that would be applicable to different arrays. By defining study-specific benchmarks *a priori,* REI results can be used to evaluate a range of questions that are customizable to specific projects. For the example herein, we formulated the REI analysis to weight all species equally, whether the tags belonged to target or nontarget species and regardless of their fishery or conservation value. Future iterations could include species-specific weighting factors for rare or endangered species, for commercially or recreationally important fishery species, or for other metrics, such as distance from release location. Likewise, tag-specific weighting factors could be applied to give greater weight to tags from nontarget species or those representing unique movements. For example, our arrays detected nurse sharks tagged in the Dry Tortugas (Pratt et al., 2018), as well as multiple shark species tagged along the Florida Atlantic coast, representing interbasin movements of individuals (D. Abercrombie pers. comm.; E. Reyier, pers. comm.). In the present example, these tags were weighted equally with all other tags, but if the research focus was to identify habitats used by highly migratory species, these tags could be given greater weight, thereby increasing the REI values for the stations at which they were detected. The ability to give nontarget detections greater weighting is an important feature of the REI method that should be especially attractive for network managers interested in identifying high-priority sites for regional monitoring. Similarly, detection data could be weighted by time (e.g., seasons, years, etc.) to highlight specific temporal periods of interest. Here we combined data across multiple years for the REI analysis, but detection data could also be subset and analyzed to determine how receiver importance may change seasonally or across years.

The two arrays we analyzed here differed in terms of spatial distribution, the ecological habitats they covered, and the specific questions they were designed to address. For example, the number of individual tags detected at each receiver was greater in the coastal array, suggesting greater movement by tagged fish between receivers, while the numbers of detections and detection days were greater in the reef array, describing high site fidelity of the detected fish. The coastal array was designed to assess large and fine scale space use to inform a mark-recapture study of red drum abundance (Lowerre-Barbieri et al., 2016b), and to assess the spatial dynamics of spawning aggregation. This large-scale monitoring effort between the Tampa Bay and Charlotte Harbor estuaries served to improve understanding of natal homing, recruitment, and reproductive timing of adults versus first-time spawners (Lowerre-Barbieri et al., 2016a). In contrast, the reef array was designed to assess the behavior and survival of two recreationally important reef-associated species after catch and release

(Collins and Barbieri, 2014, 2017). The results suggested high site fidelity for both gag and goliath grouper, where both grouper species were detected most often at or near the tagging site. Goliath grouper are known to prefer high-relief artificial structures, and some of the larger artificial reefs in the southern part of the reef array were also frequently visited by red drum and other nontarget species (Collins et al., 2015). The REI analysis corroborated high site fidelity of both gag and goliath grouper and highlighted a few large high-relief artificial structures that were also highly utilized by nontarget species (see Fig. 4). These results have already helped inform the evolution of the reef array by identifying sites with the greatest diversity of tagged species. Future iterations could upweight tags belonging to nontarget species to specifically investigate interactions between species that occur within telemetry arrays, potentially fostering novel research collaborations.

Our analysis simultaneously demonstrates the utility of regional array networks and offers justification for researchers to join these networks. Because of network affiliations we were able to identify 57.7% and 86.7% of tags that did not belong to us but were detected in the coastal and reef arrays, respectively. Both the iTAG and FACT networks facilitate connections between tag owners and array owners, iTAG through the data exchange and FACT through the shared tag metadata database. These tools allow researchers to discover where their tagged animals travel beyond the confines of a focal array and thus network arrays represent previously unavailable resources for long-range and long-term tracking. This is especially useful for researchers tracking highly migratory species. Seven of the nine nontarget species detected in the arrays were elasmobranchs (the other two were bony fishes), and some of the sharks we detected had been tagged outside of the Gulf of Mexico. Tracking animals at the interbasin or LME scale has previously been difficult and expensive, but the growth of regional telemetry networks continues to facilitate detection capacity and the development of methods like the REI analysis will assist researchers in making novel connections within their data.

4.1. Conclusions

As regional array networks grow in membership, maintaining station continuity becomes increasingly critical in providing high-value data on animal behaviors across space and time. Here we have demonstrated how the REI analysis helped us identify stations that were useful in both species-specific and network contexts. This information can be used to identify key habitats for monitoring and may guide the deployment of future arrays. The REI optimization method we describe has several advantages for researchers who need to better understand the performance of arrays and plan for future deployments. It is relatively simple analytically and generates intuitive results, can be performed during multiple points during a study, and is customizable depending on specific research priorities and array designs. The results presented here will be one component used to reorganize these two arrays as research priorities change. Although the red drum, goliath grouper, and gag studies are complete, new research projects in these areas are being developed focusing on coastal pelagic species and on inshore-to-offshore movements of maturing juveniles. As we adjust and reconfigure these arrays to address new questions, the REI analysis results revealed the stations with the highest detection value both for the study species and for nontarget species belonging to network partners. The number of researchers belonging to and gaining positive benefits from array networks will continue to grow, and we are confident that the REI approach we describe will prove a useful tool for these researchers faced with evolving their acoustic arrays.

Authorship statement

RDE, KFW, RB, JWB, and SLB conceived and designed the study; ABC, JWB, SWB, and SLB collected the data; KFW conducted the analyses; RDE drafted the manuscript; all authors contributed to manuscript revisions.

Acknowledgements

This work would not have been possible without the support of the OTN, FACT, and iTAG networks and their members. We thank Debra Abercrombie, Jayne Gardiner, Samuel Gruber, Neil Hammerschlag, Steven Kessel, Jim Locascio, Gregg Poulakis, Wes Pratt, Mike Randall, and Eric Reyier for their permission to report on the detection of their tags. Deploying and maintaining acoustic telemetry arrays in the marine environment is a significant task and the two arrays described here would not have been possible without the help of many volunteers and staff of the Florida Fish and Wildlife Research Institute (FWRI), including: Alison Brett, Jessica Carroll, Kristen Cook, Kyle McWhorter, Carlos Monzon-Aguirre, Kristen Rynerson, Josh Taylor, David Westmark, and Jamie Williams. We also thank Jennifer Herbig, Rachel Scharer, Bland Crowder, and two anonymous reviewers whose critical feedback helped improve the manuscript.

This work was supported by State of Florida fishing license sales, U.S. Department of Interior, U.S. Fish and Wildlife Service, Federal Aid for Sport Fish Restoration to the Florida Fish and Wildlife Conservation Commission. The two telemetry arrays were funded in part by National Oceanic and Atmospheric Administration Cooperative Research Program (CRP) grants NA12NMF4540079 and NA13NMF4540055 (to SLB), and MARFIN grants NA10NMF4330115 and NA13NMF4330168 (to ABC). The views, statements, conclusions, and recommendations expressed herein are those of the authors and do not necessarily reflect the opinions or policies of the U.S. government or any of its agencies.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.fishres.2018.09.015.

References

Ajemian, M.J., Mendenhall, K.S., Pollack, J.B., Wetz, M.S., Stuntz, G.W., 2018. Moving forward in a reverse estuary: habitat use and movement patterns of black drum (*Pogonias cromis*) under distinct hydrological regimes. Estuaries Coasts 41, 1410–1421. https://doi.org/10.1007/s12237-017-0363-6.

Andrews, K.S., Tolimieri, N., Williams, G.D., Samhouri, J.F., Harvey, C.J., Levin, P.S., 2011. Comparison of fine-scale acoustic monitoring systems using home range size of a demersal fish. Mar. Biol. 158, 2377–2387.

Baktoft, H., Gjelland, K.O., Økland, F., Thygesen, U.H., 2017. Positioning of aquatic animals based on time-of-arrival and random walk models using YAPS (yet another positioning solver). Sci. Rep. 7, 14294.

Boucek, R.E., Heithaus, M.R., Santos, R., Stevens, P., Rehage, J.S., 2017a. Can animal habitat use patterns influence their vulnerability to extreme climate events? An estuarine sportfish case study. Glob. Chang. Biol. 23, 4045–4057.

Boucek, R.E., Leone, E., Bickford, J., Walters-Burnsed, S., Lowerre-Barbieri, S., 2017b. More than just a spawning location: examining fine scale space use of two estuarine fish species at a spawning aggregation site. Front. Mar. Sci. 4, 355.

Clements, S., Jepsen, D., Karnowski, M., Schreck, C.B., 2005. Optimization of an acoustic telemetry array for detecting transmitter-implanted fish. N. Am. J. Fish. Manag. 25, 429–436.

Collins, A.B., 2014. An Investigation Into the Habitat, Behavior and Opportunistic Feeding Strategies of the Protected Goliath Grouper (*Epinephelus itajara*). Ph.D. Dissertation. University of South Florida, Tampa.

Collins, A.B., Barbieri, L.R., 2014. An Evaluation of the Effects of Catch and Release Angling on Survival and Behavior of Goliath Grouper (*Epinephelus itajara*) With Additional Investigation Into Residence and Long-term Movement Patterns. NOAA/NMFS Final Report #NA10NMF4330115. Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida.

Collins, A.B., Barbieri, L.R., 2017. An Evaluation of the Effects of Recreational Catch and Release Angling on the Survival of Gag Grouper (*Mycteroperca microlepis*) With Additional Investigation Into Gear and Strategies Designed to Reduce Pressure Related Fishing Trauma. NOAA/NMFS Final Report #NA 13NMF4330168. Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida.

Collins, A.B., Barbieri, L.R., McBride, R.S., McCoy, E.D., Motta, P.J., 2015. Habitat relief and volume are predictors of goliath grouper presence and abundance in the eastern Gulf of Mexico. Bul. Mar. Sci. 91, 399–418.

Cortés, E., 1997. A critical review of methods of studying fish feeding based on analysis of stomach contents: application to elasmobranch fishes. Can. J. Fish. Aquat. Sci. 54, 726–738.

Crossin, G.T., Heupel, M., Holbrook, C.M., Hussey, N., Lowerre-Barbieri, S., Nguyen, V.M., Raby, G.D., Cooke, S.J., 2017. Acoustic telemetry and fisheries management. Ecol. Appl. 27, 1031–1049.

Ellis, R., Koenig, C., Coleman, F., 2014. Spawning-related movement patterns of goliath grouper (*Epinephelus itajara*) off the Atlantic coast of Florida. Proc. 66th Gulf Caribb. Fish. Inst. 66, 395–400.

Farmer, N.A., Ault, J.S., Smith, S.G., Franklin, E.C., 2013. Methods for assessment of short-term coral reef fish movements within an acoustic array. Mov. Ecol. 1, 7–20.

Finn, J.T., Brownscombe, J.W., Haak, C.R., Cooke, S.J., Cormier, R., Gagne, T., Danylchuk, A.J., 2014. Applying network methods to acoustic telemetry data: modeling the movements of tropical marine fishes. Ecol. Model. 293, 139–149.

Guttridge, T.L., Van Zinnicq Bergmann, M.P.M., Bolte, C., Howey, L.A., Finger, J.S., Kessel, S.T., Brooks, J.L., Winram, W., Bond, M.E., Jordan, L.K.B., Cashman, R.C., Tolentino, E.R., Grubbs, R.D., Gruber, S.H., 2017. Philopatry and regional connectivity of the great hammerhead shark, *Sphyrna mokarran,* in the U.S. And Bahamas. Front. Mar. Sci. 4, 3. https://doi.org/10.3389/fmars.2017.00003.

Hart, R.K., Calver, M.C., Dickman, C.R., 2002. The index of relative importance: an alternative approach to reducing bias in descriptive studies of animal diets. Wild. Res. 29, 415–421.

Heupel, M.R., Semmens, J.M., Hobday, A.J., 2006. Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Mar. Freshw. Res. 57, 1–13.

How, J.R., de Lestang, S., 2012. Acoustic tracking: issues affecting design, analysis and interpretation of data from movement studies. Mar. Fresh. Res. 63, 312–324.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Mills Flemming, J.E., Whoriskey, F.G., 2015. Aquatic animal telemetry: a panoramic window into the underwater world. Science 348 1255642.

Jacoby, D.M.P., Brooks, E.J., Croft, D.P., Sims, D.W., 2012. Developing a deeper understanding of animal movements and spatial dynamics through novel application of network analyses. Meth. Ecol. Evol. 3, 574–583.

Kessel, S.T., Cooke, S.J., Heupel, M.R., Hussey, N.E., Simpfendorfer, C.A., Vagle, S., Fisk, A.T., 2014. A review of detection range testing in aquatic passive acoustic telemetry studies. Rev. Fish Biol. Fish. 24, 199–218.

Kraus, R.T., Holbrook, C.M., Vandergoot, C.S., Stewart, T.R., Faust, M.D., Watkinson, D.A., Charles, C., Pegg, M., Enders, E.C., Krueger, C.C., 2018. Evaluation of acoustic telemetry grids for determining aquatic animal movement and survival. Methods Ecol. Evol. 9, 1489–1502. https://doi.org/10.1111/2041-210X.12996.

Lowerre-Barbieri, S.K., Walters, S., Bickford, J., Cooper, W., Muller, R., 2013. Site fidelity and reproductive timing at a spotted seatrout spawning aggregation site: individual versus population scale behavior. Mar. Ecol. Prog. Ser. 481, 181–197.

Lowerre-Barbieri, S.K., Burnsed, S.W., Bickford, J.W., 2016a. Assessing reproductive behavior important to fisheries management: a case study with red drum, *Sciaenops oceallatus*. Ecol. Appl. 26, 979–995.

Lowerre-Barbieri, S., Tringali, M., Burnsed, S., Bickford, J., 2016b. The Red Drum (*Sciaenops ocellatus*) Spawning Population in the Eastern Gulf of Mexico: Composition, Site Fidelity, And Size. SEDAR49-DW-07. .

Lowerre-Barbieri, S., Burnsed, S., Bickford, J., Boucek, R., Staley, H., 2017. Report on the Integrated Tracking of Aquatic Animals in the Gulf of Mexico (iTAG) 2017 Workshop: Building Network Capacity. Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida.

Pecl, G.T., Tracey, S.R., Semmens, J.M., Jackson, G.D., 2006. Use of acoustic telemetry for spatial management of southern calamary *Sepioteuthis australis*, a highly mobile inshore squid species. Mar. Ecol. Prog. Ser. 328, 1–15.

Pincock, D.G., 2008. False Detections: What They Are and How to Remove Them From Detection Data. Vemco, Halifax, Nova Scotia, Canada. www.vemco.com/pdf/false_detections.pdf.

Pinkas, L.M., Oliphant, S., Iverson, I.L.K., 1971. Food habits of albacore, bluefin tuna and bonito in Californian waters. Calif. Fish Game 152, 1–105.

Pratt Jr., H.L., Pratt, T.C., Morley, D., Lowerre-Barbieri, S., Collins, A.B., Carrier, J.C., Hart, K.M., Whitney, N.M., 2018. Partial migration of the nurse shark, *Ginglymostoma cirratum* (Bonnaterre), from the Dry Tortugas Islands. Environ. Biol. Fish. 101, 515–530. https://doi.org/10.1007/s10641-017-0711-1.

Simpfendorfer, C.A., Heupel, M.R., Hueter, R.E., 2002. Estimation of short-term centers of activity from an array of omnidirectional hydrophones and its use in studying animal movements. Can. J. Fish. Aquat. Sci. 59, 23–32.

Steckenreuter, A., Hoenner, X., Huveneers, C., Simpfendorfer, C., Buscot, M.J., Tattersall, K., Babcock, R., Heupel, M., Meekan, M., van den Broek, J., McDowall, P., Peddemors, V., Harcourt, R., 2017. Optimising the design of large-scale acoustic telemetry curtains. Mar. Freshw. Res. 68, 1403–1413. https://doi.org/10.1071/MF16126.

Walters, S., Lowerre-Barbieri, S., Bickford, J., Tustison, J., Landberg, J.H., 2013. Effects of *Karenia brevis* red tide on the spatial distribution of spawning aggregations of sand seatrout *Cynoscion arenarius* in Tampa Bay, Florida. Mar. Ecol. Prog. Ser. 479, 191–202. https://doi.org/10.3354/meps10219.

Welsh, J.Q., Fox, R.J., Webber, D.M., Bellwood, D.R., 2012. Performance of remote acoustic receivers within a coral reef habitat: implications for array design. Coral Reefs 31, 693–702.